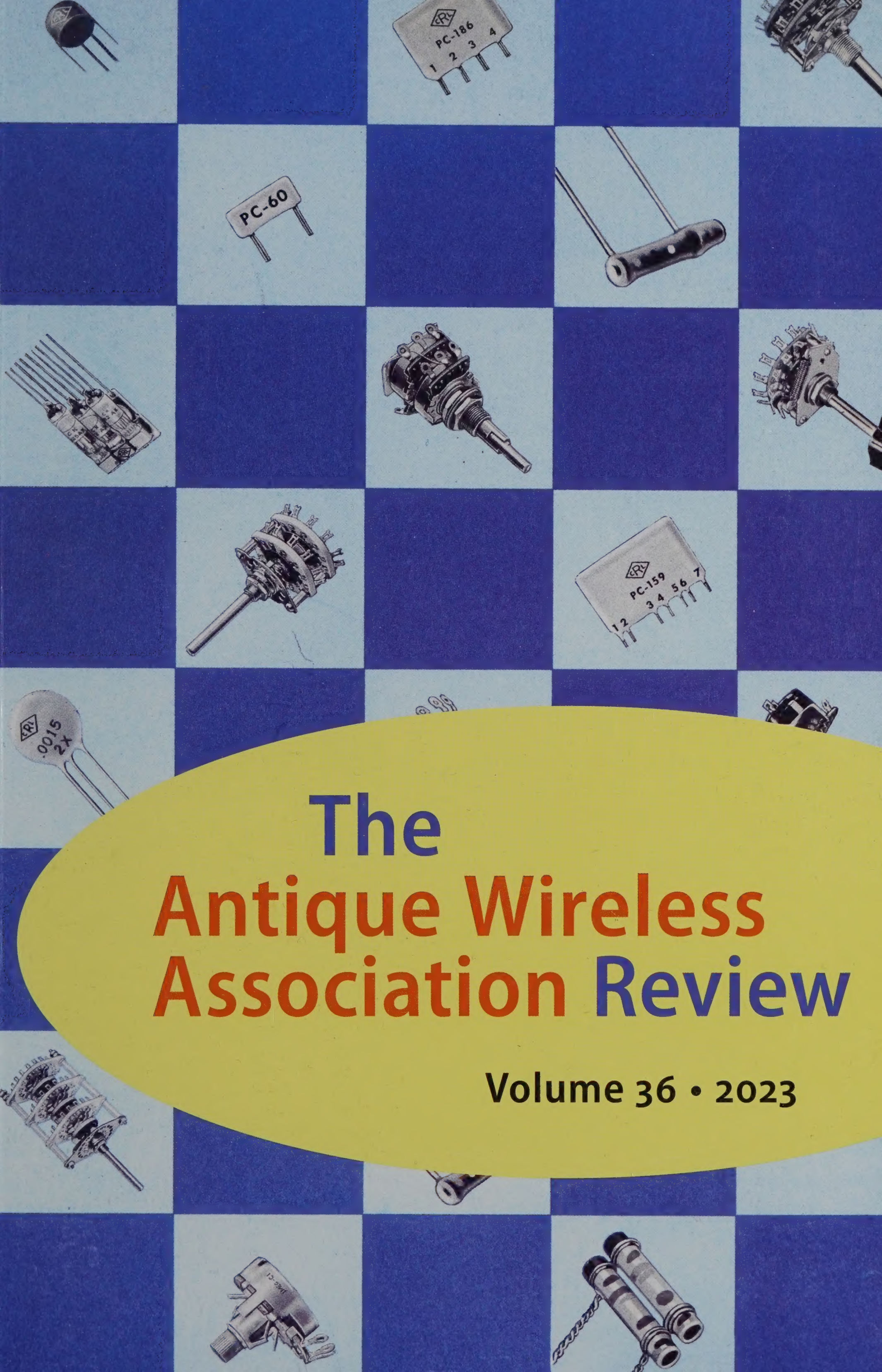

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Cover Images: The front cover shows a collage of electrical components available from Centralab in their 1957 catalog. The back cover shows the cover of Centralab PEC Guide No. 3, a booklet having part listings, schematics, and test data for the latest series of Centralab inovations: the printed electronic circuit. Front cover image: Centralab Electronics Components catalog 30. Back cover image: Centralab PEC Guide No. 3.

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Foreword

Wow! Again, we are fortunate to have many interesting, well-written, well-researched, and unique articles recounting various events, people, companies, inventions, technologies, and milestones in the history of electronic communication. Below is a summary of each of the articles in the order that they appear.

- **Glenn Trischan** continues the story of the history of Central Radio Laboratory (Centralab) in the period from 1940 to 1959, during which time the company experienced unprecedented growth. The major milestones in Centralab's history and an abbreviated look at their product evolution between 1940 and 1959 are documented. This is an incredible history that Glenn has compiled, and we are grateful for the historical preservation of the Centralab story. The evolution of these inventions and discoveries changed the world. The young talent of Jack Kilby is shown during his time at Centralab, but then he leaves for Texas Instruments and on to invent a really big thing. The essence of Jack Kilby's transition from Centralab to TI has been very wonderfully captured.

- **Jerry Proc** describes equipment and techniques to locate radio transmitters and identify transmission sites, operators, and transmitting equipment during World War II. The most common method was radio direction finding, but there were at least two other techniques that could provide data or intelligence about the characteristics of the transmitter making the transmission and the Morse code style of the operator. These techniques were known as Radio Fingerprinting and a code-named process called TINA, both of which were used by the Allies. (TINA was derived from the last four letters of the word "Serpentina," a name used for the method of recording hand-sent Morse transmissions on paper tape for later analysis.) When used together, these were known as "Z" intelligence in the British Commonwealth countries. Finally, the methods and results of noise investigation used to assess technological improvements, especially by enemy radar, are described.

- **Eric Wenaas** examines claims regarding the invention of radio tubes by Lee De Forest. He begins with an account of how De Forest developed his two-electrode audion, a development that he claimed was an integral step in the development of the three-electrode audion. De Forest published two extensive but conflicting accounts about how he developed his two-electrode audion, one at a lecture in October 1906, and the other at a lecture fourteen years later. The differences between these two accounts are dramatic and cast doubt on the credibility of both. De Forest also provided a third and very different account that surfaced during a lawsuit filed by American Marconi in 1914 alleging that De Forest's audions infringed Fleming's valve patent. The testimony and exhibits from the trial were documented for the participants in the lawsuits and court records, but they were never made public. The testimony and exhibits prepared for the plaintiff's attorney became available recently, so a very different version of how De Forest developed his two-electrode audion can now be told.

- **David and Julia Bart** give a history of early satellite communications by showing the development of Bell Laboratories' giant horn antennas at the Andover Earth Station in Maine and Crawford Hill Earth Station in New Jersey. The Telstar satellite relied on these and other ground antennas to communicate from orbit to Earth. Telstar allowed the first live broadcast of television images between the United States and Europe in 1962. The two giant horn antennas were used after Telstar for research and other satellite communications. The Crawford Hill horn antenna later played a pivotal role in the serendipitous discovery of cosmic microwave background radiation that permeates the universe, therefore proving the Big Bang theory, and leading to the Nobel Prize in Physics being awarded to the two researchers. The Andover horn antenna was dismantled in the mid-1980s, but the Andover Earth Station there continues to operate as part of Verizon's Satellite Solution Group.

- **Richard Brewster** tells the story of how television grew between 1929 and 1939 from a laboratory curiosity to a commercially viable system. This paper shows via one specific trail how each iteration of the home TV set made that transition in very deliberate steps. The television receiver here is defined as a complete package that receives radio-frequency transmitted audio and video images, complete with appropriate synchronizing information, and displays these images using a completely electronic system.

- **Sreeram Dhurjaty** discusses a class of loudspeakers categorized as transmission line loudspeakers. This loudspeaker design was described by Benjamin Olney in a 1936 patent. His employer, Stromberg-Carlson, used this design in radio receivers they built. The transmission line loudspeaker is a labyrinth that was the first of its kind. The goal of early loudspeaker design was to modify and suppress acoustic radiation from the rear of the speaker driver so that there was an improvement in bass. In 1984 a class of loudspeakers was introduced by Bose and labeled acoustic wave speakers. Rather than suppressing the radiation from the rear of the driver, a means was provided, using standing waves, to take advantage of radiation from both the front and rear of the driver and add them constructively. This method produced a very good bass response in a small cabinet size with good efficiency. The science and operation of transmission line speakers is the subject of this review. Analogs between acoustic transmission lines and electromagnetic transmission lines are described.

- **Robert Rydzewski** has researched the life of radio pioneer Robert Gowen. Working for Dr. Lee De Forest, Gowen invented the concept of the interpanel receiver, the honeycomb coil, and improvements to the audion. An avid amateur, he pursued the ever-elusive DX, establishing experimental radiotelephony station 2XX at his Ossining, New York home. He soon set distance records and become one of the earliest radio broadcasters. Leaving De Forest's employ, he went to China where he installed radiotelephone stations. Knowing not a word of Chinese, and with few supplies available, he was also tasked with writing a training manual and teaching the locals how to operate and maintain their stations. The presentation of this remarkable tale of his life is started here in Part 1 with Gowen's earliest radio experiments, his college years at Harvard, his post-college experiences in radio and electronics, and his initial experiences with Lee De Forest. (Part 2 will continue the story in a future issue.)

We thank all of our authors for sharing their work with us. I thank each one of them for the cordial interactions we have had while preparing the manuscripts. I also want to thank our associate editor, Eric Wenaas, and our peer reviewers who have worked so hard and given so much time to review and edit these papers. Finally, I would like to thank Fiona Raven for the wonderful article layouts that we have come to expect each year—and especially for the original layouts on the covers of the *AWA Review*. Fiona's professional and creative work never ceases to amaze, and she makes all our authors look great.

Several years ago, the AWA created the Robert P. Murray Award in honor of Robert Murray, long-time *AWA Review* editor, and now Editor Emeritus, for excellence in writing in the *AWA Review*. The fifth award was presented at the AWA conference in Rochester in 2022 to Eric Wenaas. Congratulations to Eric for a job well done; we know he will continue to write high-quality articles in the future.

This is my fourth year as editor. I have greatly enjoyed this assignment and look forward to editing future editions. I hope my effort meets or exceeds the quality you have come to expect. My professional background as a systems engineer in major high-tech companies developing military weapons systems has prepared me to pay attention to the detail needed and meet the workload and scheduling requirements. My life-long amateur radio hobby and interest in all things electronic has provided a deep and yet broad background in radio communications and electronics of all kinds.

Tim Martin, WB2VVQ
Editor, *AWA Review*
Lee, MA

Tips for Authors

The AWA Review invites previously unpublished papers on electronic communication history and associated artifacts, with a focus on antique wireless. Papers will be peer-reviewed to verify factual content by peer reviewers whose identities will remain anonymous. This process gives the *AWA Review* credibility as a source of correct historical information. The papers will be edited to provide uniformity in style and layout among the articles. In general, shorter articles of five pages of text (2,500 words and a few pictures) or less should be directed toward the *AWA Journal*, which is published quarterly. The *AWA Review* is intended for longer articles on the order of 3,000 to 25,000 words and many pictures. Longer articles may be accepted or may be split into parts for publication over several years.

The *AWA Review* will also publish letters to the editor as deemed appropriate. Letters should comment on articles published in the previous issue of the *AWA Review* or make brief comments on wireless history as it relates to one of the articles. Letters will not be peer-reviewed, but they may be edited. Text is limited as determined by the editor. The editor reserves the right to publish responses to letters.

It is strongly recommended that authors planning to prepare an article for the *AWA Review* send an abstract of approximately 200 words to the editor describing the subject and scope of the paper before writing the article, including an estimate of the number of words. It is never too early to submit an abstract. Space in the *AWA Review* is not unlimited, so both editors and authors alike need to have an estimate of the expected number of articles and the number of pages for each article as soon as possible. The deadline for submissions of manuscripts in the next issue is February 1, 2024. Papers will be accepted after that, but papers submitted and accepted for publication before February 1 will have priority if there is no space for all papers submitted.

Authors with an interesting story should not be discouraged by a lack of writing experience or knowledge about writing styles. The *AWA Review* will accept manuscripts in any prepared writing style. Editors will help inexperienced authors with paper organization, writing style, reference citations, and improvements in image quality. Edited manuscripts will be returned to the author along with comments from the editor and anonymous reviewers for the author's review and comment. The manuscript will then be set in its final form and sent back for one final review by the author. Normally, only one review of the layout will be accommodated.

To summarize, please submit completed manuscripts by February 1, 2024 (or earlier if possible) in three separate files:

1) A manuscript file without embedded figures or figure captions using Microsoft Word or other software that is compatible with Word. The manuscript should have an abstract of approximately 200 words, a main body with endnote citations

and endnotes, acknowledgements, and paragraphs summarizing the author's background. The author should also enclose a recent photograph focusing on the head and shoulders.

2) Figures, with one figure per file, with the numbering of figures and files that match the figure callouts. A callout to the figures must appear in at least one sentence of the manuscript text.

3) A figure caption file with a description of each figure and an attribution identifying its source. For more information, consult the AWA website at http://www.antiquewireless.org/awa-review-submissions.html. Please feel free to contact me as editor for the *AWA Review* for any questions.

Timothy Martin, BE, ME, PE
AWA Review Editor for 2023
Email: AWAReviewEditor@AntiqueWireless.org

The Centralab Story: Innovations and Growth, 1940–1959

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The Centralab story is one of many successes along with significant near misses in the American electronics industry. Having survived the Great Depression and vagaries of World War II, Centralab experienced unprecedented growth only to encounter an evolving industry and marketplace. The major milestones in Centralab's history and an abbreviated look at their product evolution between 1940 and 1959 are documented. The Centralab story has been constructed from a variety of written essays, internal company documents, and product literature. Given the diversity and evolution of their products, no attempt has been made to present a comprehensive summary of product designs, manufacturing dates, or variations.

Background

Founded as the Central Radio Laboratories in 1922, the business survived the exhaustion of its initial capital through the sale of the company in 1925 to a much larger manufacturing organization, Globe Electric Company. Under new ownership, the renamed Centralab organization not only survived the Great Depression of the 1930s but expanded its product lines and grew its customer base as the domestic radio business steadily recovered. The early history, product development, and evolution through 1939 have been presented in a previous article.[1]

The Centralab Division of Globe-Union entered the 1940s with a growing portfolio of electronic component offerings and an increasing base of radio and electronic customers. While the business was growing, changes in the global political climate would soon dictate significant changes to the future of the business. Evolutionary changes through the ensuing two decades would eventually lead to investigations of semiconductor production, development of miniature low-voltage products for transistor circuit applications, a near miss with respect to the invention of the integrated circuit, and the start of an unprecedented global migration of the U.S. electronics industry to Asian locations.

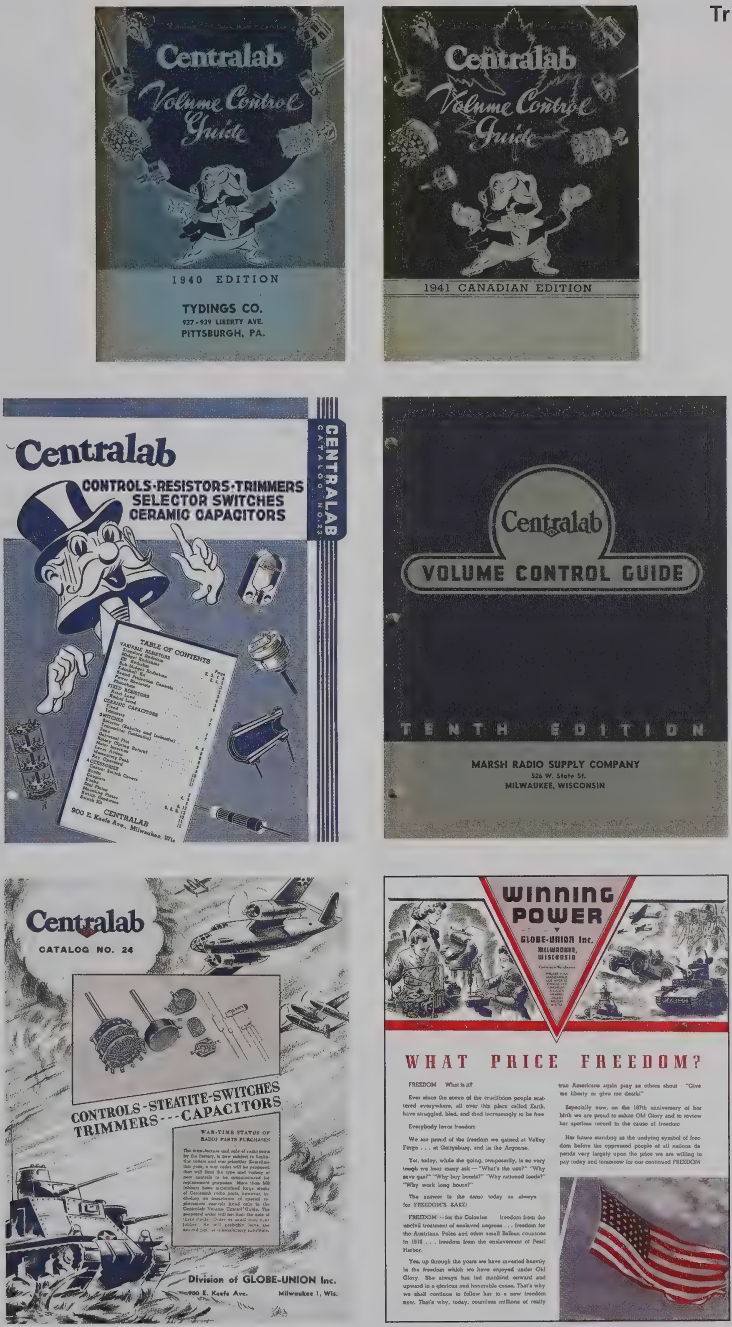
The War Years: 1940–1945

The year 1940 found Centralab supplying a growing variety of fixed and variable resistances, switches, and ceramic capacitors to the OEM, repair, and amateur markets. These products are well represented in product catalogs, the popular Centralab *Volume Control Guides* and catalogs, as well as advertising literature found in magazines such as *Radio News*, *QST*, and other publications. The 1940 *Volume Control Guide* (Fig. 1) had expanded to 219 pages using a larger 5" × 7" format compared to previous "pocket" editions. Much like previous editions, the bulk of the volume (164 pages) was devoted to replacement variable resistances for radio volume and tone controls. The balance contained product information on variable resistances for audio/visual and OEM applications, fixed resistors, switches, and temperature-compensating tubular ceramic capacitors.[2] Older products making their final appearances included the "Phonohm," originally introduced in the 1920s as an in-line headphone volume control, and auto radio noise suppressor resistances. An abbreviated version of this *Volume Control Guide* was issued in a Canadian edition dated 1941, which incorporated a maple leaf in the cover design (also in Fig. 1). This edition consisted of only 89 pages and appears to be directed specifically to Canadian radio replacement volume controls.[3] Product offerings in both the United States and Canadian volumes essentially duplicated those found in their 1939 literature. Similarly, catalog No. 23, in Fig. 1, a 12-page compendium of product offerings dated May 1941, did not offer any significant new developments. This would be the last appearance of the "Old Man Centralab" mascot in factory literature,[4] although he would appear in a variety of print ads through 1945.

During the period 1939–1941, several changes in production footprint occurred. At the request of the U.S. Navy, technical ceramics production was expanded through the enlargement of the main Keefe Avenue plant. Plans were initiated to lease additional space for anticipated wartime production demands.[5]

The 10th edition of the Centralab *Volume Control Guide* dated January 1942 (Fig. 1), was clearly prepared before the events of December 7, 1941. An insert pasted to the front page acknowledged the evolving uncertainties of war austerities, noting that the use of copper, brass, and bronze had been discontinued where they were not incorporated in an electronic circuit. Similarly, aluminum, as well as brass, had been eliminated from all shafts on replacement controls and switches and replaced with steel, which "will present no difficulty if a sharp hacksaw is used to cut the shaft."[6] This issue of the *Volume Control Guide* ran to 70,000 copies and marked the first time that the guide had grown into a full 8½ × 11 format containing 128 pages of product information, primarily for volume controls for some 21,000 different receiver models.[7] One noteworthy change was replacement of the diamond motif used on Centralab boxes with a simpler blue background with silver or white corner lines as shown in an unusual ad that included the packaging for the midget Radiohm.[8] Selector switches, fixed temperature compensating ceramic capacitors, trimmers, radial and axial fixed resistors, and audio-visual controls were also represented.

A big change in the product line occurred in 1942. Centralab was the first manufacturer to produce steatite insulating materials that exceeded the Army/Navy grade requirements. Accordingly,



WAR-TIME STATUS OF RADIO PARTS PURCHASES

The manufacture and sale of radio parts by the factory, is now subject to limitation orders and war priorities. Sometime this year, a war order will be proposed that will limit the type and variety of new controls to be manufactured for replacement purposes. More than 500 jobbers have maintained large stocks of Centralab radio parts, however, including an assortment of special replacement controls listed only in the Centralab Volume Control Guide. The proposed order will not limit the sale of these stocks. Order as usual from your jobber. He will probably have the desired part or a satisfactory substitute.

WHAT PRICE FREEDOM?

FREEDOM What is it?

Ever since the scene of the crucifixion people scattered everywhere, all over this place called Earth, have struggled, bled, and died increasingly to be free.

Everybody loves freedom.

We are proud of the freedom we gained at Valley Forge . . . at Gettysburg, and in the Argonne.

Yet, today, while the going, temporarily, is so very tough we hear many ask — "What's the use?" "Why save gas?" "Why buy bonds?" "Why rationed foods?" "Why work long hours?"

The answer is the same today as always for FREEDOM'S SAKE!

FREEDOM — for the Colonies . . . freedom from the uncivil treatment of enslaved negroes . . . freedom for the Austrians, Poles and other small Balkan countries in 1918 . . . freedom from the enslavement of Pearl Harbor.

Yes, up through the years we have invested heavily in the freedom which we have enjoyed under Old Glory. She always has led mankind onward and upward in a glorious and honorable cause. That's why we shall continue to follow her to a new freedom now. That's why, today, countless millions of really true Americans again pray as others about . "Give me liberty or give me death!"

Especially now, on the 167th anniversary of her birth we are proud to salute Old Glory and to review her spotless record in the cause of freedom.

Her future standing as the undying symbol of freedom before the oppressed people of all nations depends very largely upon the price we are willing to pay today and tomorrow for our continued FREEDOM.

Fig. 1. Centralab *Volume Control Guide*, May 1940; 1941 Canadian edition Centralab *Volume Control Guide; Centralab* catalog No. 23, May 1941; Centralab *Volume Control Guide*, 10th edition, Jan. 1942: *Centralab* catalog No. 24, July 1943; Illustrated cover of *Winning Power*, Vol. 1, No. 9, July 1943. (Author's collection)

the U.S. Armed Forces approached Centralab to expand its ceramic production capacity. The Centralab fixed resistor line was discontinued, since alternate manufacturers were available. Centralab's fixed resistor production equipment was repurposed for production of temperature-compensating capacitors to meet anticipated military needs. An additional plant was built to produce steatite-insulating ceramics. From no production capacity in 1942, Centralab's steatite ceramic business bloomed to an average of $255,000 per month in 1943 and 1944.[9]

To meet the war effort, Centralab developed a flat ceramic capacitor and was the sole source of high-accuracy hermetically sealed units. Centralab was also the sole source of ceramic RF band change switches until the closing year of the war. In addition, Centralab was the sole source for variable resistors in both the Link Aviation Pilot Trainers and the General Electric fire control computer for use in the 50 caliber antiaircraft machine gun.[10]

By July 1943, catalog No. 24 was issued, which clearly reflected the wartime conditions (Fig. 1). A variety of variable resistances, switches, fixed capacitors, and trimmers were presented, although civilian availability was limited.[11] Similarly, to conserve resources, advertising continued to appear in publications such as *QST* on a limited basis to maintain name recognition for the duration of the war. As would be expected, Centralab's new products were not introduced, and the most important Centralab activities to support the war effort were kept out of sight and not mentioned.

One contemporary internal Globe-Union publication for employees and ex-employee service members appeared beginning in November 1942. Entitled *Winning Power*, its name was a play on the Globe auto battery motto "Spinning Power." The publication appears to have run about three volumes through the war's end in 1945. Each volume included a patriotic cover message and images, as shown in bottom right of Fig. 1.[12] While most contents related to service members, employees, and general "win the war" activities, several interesting Centralab items were found in the few surviving issues. While the photos do not show activities close-up, and the descriptions are bland, a sense of the working environment is evident. Production activities in the Silver Mica Condenser Department are shown in Fig. 2.[13] An example of activities in the Ceramics Department appears in Fig. 3, which illustrates the mass cut-off operations before firing.[14] A new production facility at 3238 N. Bremen St. (Badger plant), celebrated a housewarming gala on April 3, 1943. Globe-Union President C. O. Wanvig, Sr. is shown giving opening remarks to employees in Fig. 4.[15] Surprisingly, some of the new Badger plant activities appeared three months later. The new air-conditioned testing lab is illustrated in Fig. 5.[16]

Not all was work and war. The Junior Achievement Players ensemble sponsored by Globe-Union for the Globe Radio Playhouse is shown in Fig. 6. The group performed a series of 30 minute

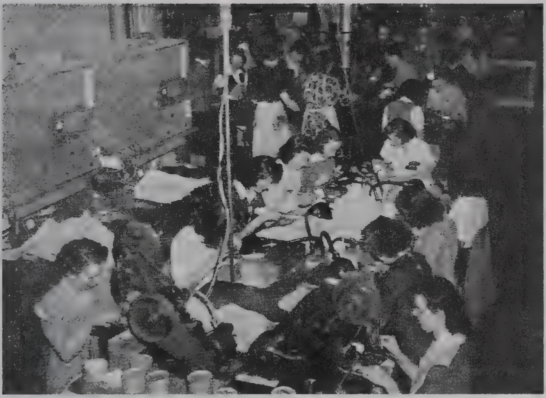


Fig. 2. Centralab Silver Mica Condenser Department. (*Winning Power*, Vol. 1, No. 4, Globe-Union, Inc, Feb. 1943)

Fig. 4. C. O. Wanvig at Badger plant housewarming. (*Winning Power*, Vol. 1, No. 5, Globe-Union, Inc., Mar. 1943)

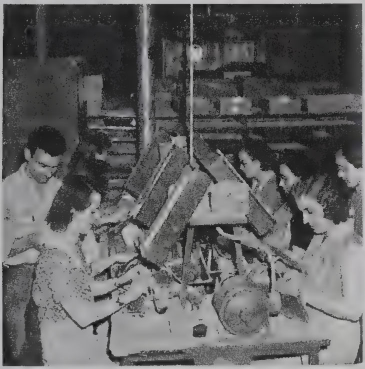


Fig. 3. Centralab Ceramics Department. (*Winning Power*, Vol. 1, No. 5, Globe-Union, Inc., Mar. 1943)

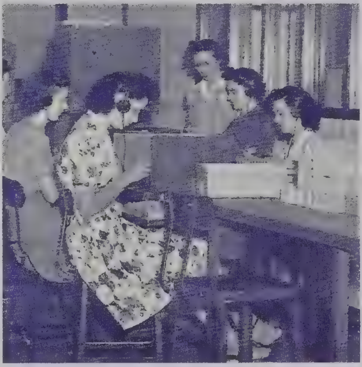


Fig. 5. Centralab testing lab at the new Badger plant. (*Winning Power*, Vol. 1, No. 9, Globe-Union, Inc., July 1943)

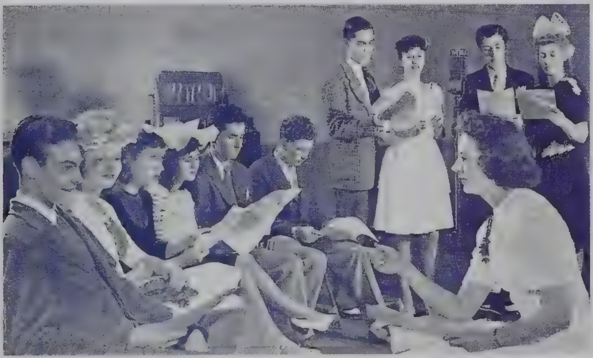


Fig. 6. Globe Radio Playhouse Junior Achievement Players Group. (*Winning Power*, Vol. 1, No. 9, Globe-Union, Inc., July 1943)

radio programs of comedy and drama through the summer of 1943 on Milwaukee radio station WTMJ and Chicago station WBBM. Programs were jointly directed by Virginia Bartelt (Wisconsin School of Music) and Kenneth Greaves (Globe-Union). Bob Hanson, a Globe engineer that was formerly part of the WTMJ staff, did the program announcing. Broadcasts were scheduled between 4:00 and 4:30 p.m. on Sundays.[17] An in-studio photo of a live performance is shown in Fig. 7.[18]

Aside from their standard and military product lines, Centralab made two contributions to the development of proximity fuses. The proximity fuse was one of the more significant advances in military ordnance in that the shell could be detonated at a set distance from its target, rather than having to make physical contact with its objective.[19] The initial CRL contribution to the war effort consisted of an improved safety switch for the airborne M-8 rocket. The more far-reaching Centralab technology was developed in support of the VTM 81 mm mortar radio proximity fuse for attacks on Japanese foxholes.[20] The successful fuse was required to survive a 10,000 g-force generated during the mortar launch while fitting in one-third of the space of a conventional proximity fuse.[21] To meet the need, Centralab employees Rubenstein, Ehlers, Sherwood, and White proposed to build a device consisting of a ceramic substrate having affixed chip capacitors and conductive paths that could be attached to miniature vacuum tubes.[22] A complete mortar with the proximity fuse attached is shown in Fig. 8.[23] The approximate size and location of the Centralab component can be seen in Fig. 9, which also shows a comparison to a 6L6G vacuum tube.[24] By V-J Day, September 2, 1945, the production of 100,000 proximity fuses per month started using a proprietary process that will be discussed later.[25]

Fig. 7. Globe Radio Playhouse Players in the studio. (*Winning Power*, Vol. 1, No. 12, Globe-Union, Inc., Oct. 1943)

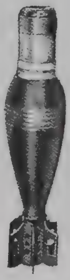


Fig. 8. VTM 81 mm mortar shell. (*Centralab PEC Basic Data*, Centralab Form 42-1281, Centralab Division of Globe-Union, Inc., ca. 1960)

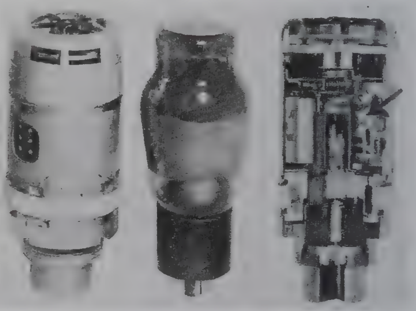


Fig. 9. Proximity fuse showing Centralab PEC location and comparison to 6L6G vacuum tube. (*Electronics*, Apr. 1946)

No time was wasted at the conclusion of the war to get Centralab product information into the hands of potential customers. Initially, catalog No. 24 from 1943 was reprinted in April 1946 with a print run of 10,000 copies. The only edit from the original printing was the deletion of the insulated capacitor product.[26] This catalog was quickly followed by the publication of catalog No. 25 in May 1946 with a print run of 70,000 (see Fig. 10).[27] Several significant product line changes occurred.

The year 1947 would prove to be auspicious for both Centralab and the electronics world. After the government declassified much of the work that Centralab was doing, the company would transition its military experience with ceramics and conductive screen-printing to launch a new product line, Printed Electronic Circuits (PECs). The PEC products were targeted to the burgeoning consumer demands for radios, televisions, and other applications where special constraints were critical. To that end, the Centralab engineering staff was expanded with many new hires, including a freshly minted electrical engineer named Jack St. Clair Kilby.[28] His initial assignment was to perform design and product engineering on the screen-printed circuits for use in hearing aid amplifiers and RC networks.[29]

Fig. 10. *Centralab* general catalog No. 25, Centralab Form 1001, May 1946. (Author)

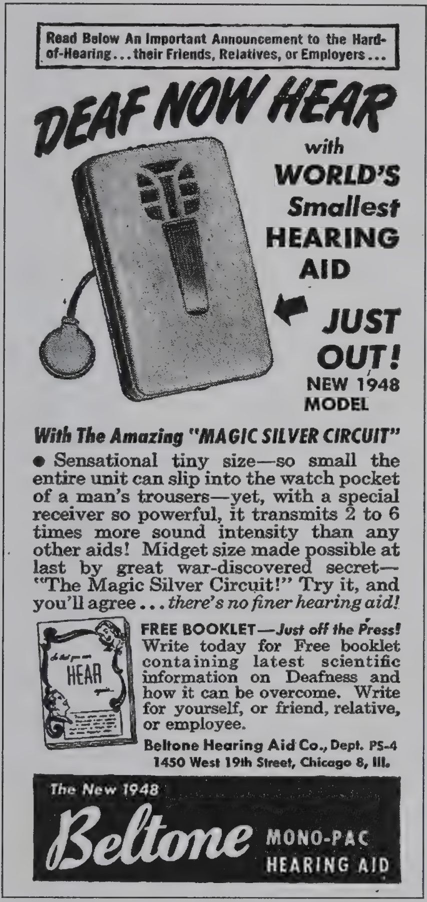
With the announcement of the first solid-state "triode," or transistor, by Bardeen, Brattain, and Shockley on December 23, 1947, the era of solid-state electronics was born, which would lead to unprecedented and unimaginable developments. This development would prove to be a fertile field for Jack S. Kilby, engineer and inventor. While we will focus on Jack Kilby's activities, the next 30 years of revolutionary developments in electronics are amply presented elsewhere.[30]

PECs: Printed/Packaged Electronic Circuits

Once the security classification changed, Centralab wasted no time in publicizing its new development. On February 8, 1946, Dr. Cledo Brunetti, Chief of Project Engineering at the National Bureau of Standards, described the device to the Milwaukee Subsection of the Institute of Radio Engineers meeting at Marquette University. His remarks concluded that Globe-Union at the time had perfected the circuit.[31] What followed was a barrage of newspaper and periodical publications regarding the new development. In an attempt to garner public attention, by early 1947 a two-tube "vest pocket" radio designed around the small circuit, christened "Couplate," was announced. Mass production of the Couplate was anticipated by mid-summer 1947. Centralab accepted orders and provided samples to radio engineers.[32] Some Centralab advertising went so far as to tout this product as "The war's secret weapon No. 2."[33]

Centralab's key wartime innovation for the proximity fuse was quickly adapted to high-volume screening techniques for civilian uses with the dedication of substantial resources to produce trademarked Printed Electronic Circuits (PECs) under the direction of R. L. Wolff and A. S. Khouri.[34] These devices consisted of one or more passive components (resistors and capacitors) interconnected by silver conductors applied to a solid ceramic substrate, using a process very much like silk screening.[35] The completed device was subsequently coated with a protective encapsulation.[36] The process details are described in several post-war publications.[37] Essentially a dielectric substrate made of steatite was prepared in an appropriate die of the proper size to accommodate all circuit components without crossover of any conductors. Through holes were created using pins inserted in the die. After forming the raw baseplate, the material was fused at 2400 °F. A 10% shrinkage and some degree of warpage were anticipated. The surface to be printed was ground flat with a diamond wheel or lap grinder. Following the preparation of an appropriate printing mask, silver paint was applied to the substrate via a screen printing process and fired at 1500 °F. Resistors were subsequently printed in contact with the appropriate silver conductors on the baseplate and baked to produce a carbon path. Resistors of the same value were printed in a single step. Resistances were generally adjusted by altering the carbon content of the ink, although adjustments in the carbon path length could be made within limits. The baseplate was coated with phenolic at this point, leaving an exposed conductor for the attachment of capacitors or connectors. After baking to set the phenolic, the exposed conductors were dipped in solder for tinning. Titanate capacitors were sweat-soldered in place and the entire assembly was coated in sealant, usually a phenolic material.[38] As the technology matured, detailed considerations of process design, materials, and equipment were discussed in a later publication.[39]

Centralab's civilian Printed Electronic Circuit (PEC) line was first mentioned in the 11th edition of the *Volume Control Guide*.[40] By 1948, a unique application of the PEC was made in the Beltone hearing aid. A specially designed PEC was used to incorporate multiple components on a single substrate for a three-tube amplifier using Raytheon subminiature tubes.[41] The new hearing aid offered the best of both worlds, uniquely compact, lightweight, and with long battery life—all in one case. Beltone and Centralab ads appeared in several publications, including *Popular Science*, where the "Magic Silver Circuit" was described as a "great war-discovered secret" in Fig. 11.[42] A contemporary Centralab ad appeared in *Electronics* showing



Read Below An Important Announcement to the Hard-of-Hearing . . . their Friends, Relatives, or Employers . . .

DEAF NOW HEAR

with **WORLD'S Smallest HEARING AID**

JUST OUT!

NEW 1948 MODEL

With The Amazing "MAGIC SILVER CIRCUIT"

- Sensational tiny size—so small the entire unit can slip into the watch pocket of a man's trousers—yet, with a special receiver so powerful, it transmits 2 to 6 times more sound intensity than any other aids! Midget size made possible at last by great war-discovered secret—"The Magic Silver Circuit!" Try it, and you'll agree . . . *there's no finer hearing aid!*

FREE BOOKLET—*Just off the Press!* Write today for Free booklet containing latest scientific information on Deafness and how it can be overcome. Write for yourself, or friend, relative, or employee.

Beltone Hearing Aid Co., Dept. PS-4
1450 West 19th Street, Chicago 8, Ill.

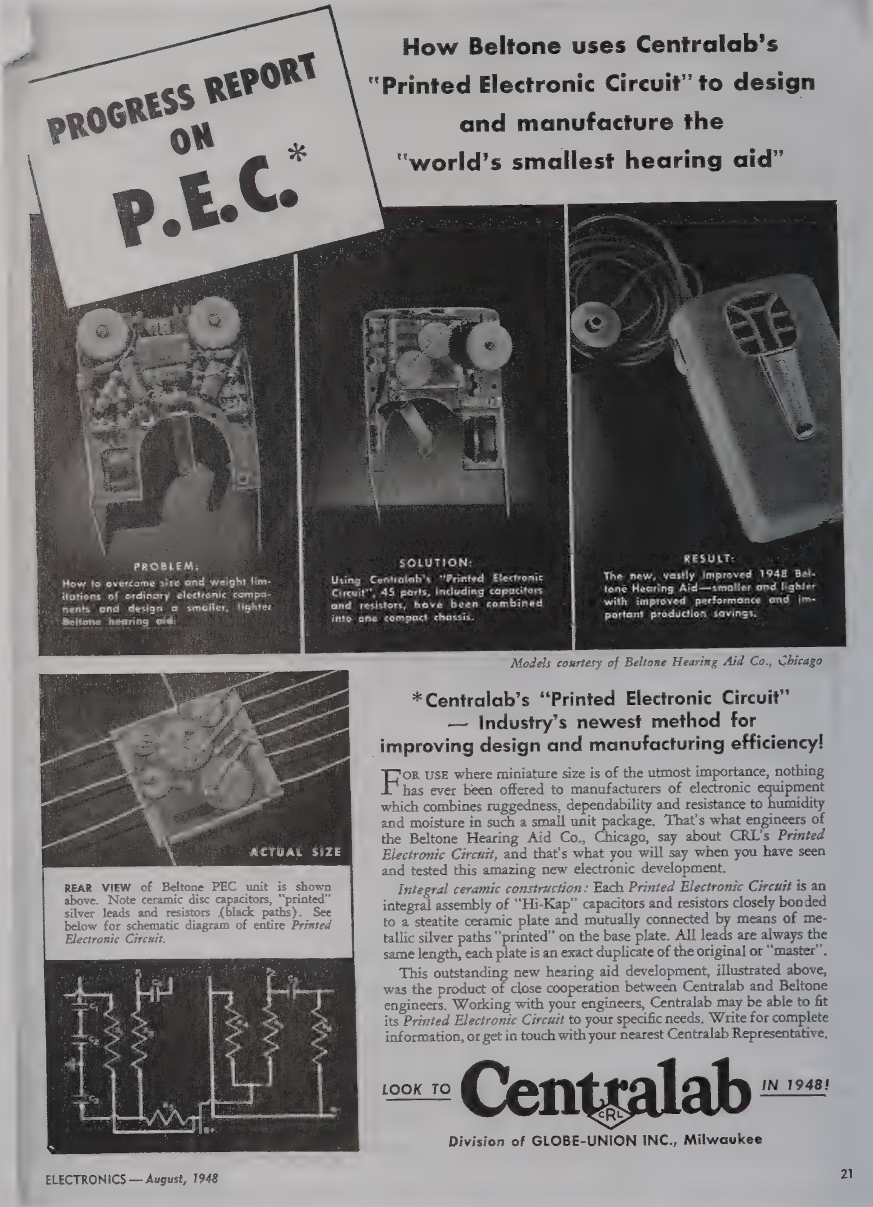
The New 1948 **Beltone** MONO-PAC HEARING AID

Fig. 11. Beltone hearing aid advertisement announcing Centralab PEC. (*Popular Science*, 1948, unspecified issue)

a more detailed description including a photo of the PEC and generic circuit diagram (Fig. 12).[43] By 1950, over 60% of all hearing aids used the PEC design.[44] An example of the 1948 Beltone Symphonette hearing aid is compared to both the Sony TR-63 transistor radio and the 1956 five-transistor Beltone Fortissimo hearing aid (see Fig. 13).

General purpose and custom OEM PECs would proliferate in step with the boom in consumer electronics and corresponding OEM drives for size and cost reductions in the coming decade. Although manufactured by automated production processes, the key process, screening the circuit conductors or resistors onto the ceramic substrate by manual application, is shown in Fig. 14. By 1951, some 15 million PECs were in use. Cost savings were attributed to reduced OEM inventories and a reduced number of required solder connections. While the latter is true in many cases, the PEC-2, which consisted of a single resistor, clearly was an exception to both attributes. In this case, the humidity stability offered by the Durez coating appears to be the primary incentive for its use.[45]

By 1948, multi-page ads illustrated actual PEC installations in radios, including Sonora, as well as Beltone hearing aids, with emphasis on compact size, reduced production soldering, humidity resistance, and long life.[46] An example of a Filpec (electronic circuit filter PEC) incorporating a two-capacitor, one-resistor network inside of a Sickles miniature IF transformer was illustrated. Available ranges of capacitors were 50 to 200 pF and ⅕ watt resistances of 5 ohms to 5 megohms at 100 WVDC. Additional details were available in Centralab *Bulletin* 976.[47] This was followed up with illustrations of a Sentinel radio chassis incorporating a Centralab Couplate (interstage coupling plate PEC) and a Filpec.[48] By July 1948, a Stewart-Warner chassis exhibited a *tour de force* of Centralab components including PECs, sliding switch, and multiple tubular, disc, and temperature compensating capacitors.[49] By August 1948, the Centralab printed electronic circuits garnered a full-color illustration on the cover of *Electronics*, as shown in



ACTUAL SIZE

PROGRESS REPORT ON P.E.C.*

How Beltone uses Centralab's "Printed Electronic Circuit" to design and manufacture the "world's smallest hearing aid"

PROBLEM:
How to overcame size and weight limitations of ordinary electronic components and design a smaller, lighter Beltone hearing aid.

SOLUTION:
Using Centralab's "Printed Electronic Circuit", 45 parts, including capacitors and resistors, have been combined into one compact chassis.

RESULT:
The new, vastly improved 1948 Beltone Hearing Aid—smaller and lighter with improved performance and important production savings.

Models courtesy of Beltone Hearing Aid Co., Chicago

REAR VIEW of Beltone PEC unit is shown above. Note ceramic disc capacitors, "printed" silver leads and resistors .(black paths). See below for schematic diagram of entire *Printed Electronic Circuit.*

***Centralab's "Printed Electronic Circuit" — Industry's newest method for improving design and manufacturing efficiency!**

FOR USE where miniature size is of the utmost importance, nothing has ever been offered to manufacturers of electronic equipment which combines ruggedness, dependability and resistance to humidity and moisture in such a small unit package. That's what engineers of the Beltone Hearing Aid Co., Chicago, say about CRL's *Printed Electronic Circuit*, and that's what you will say when you have seen and tested this amazing new electronic development.

Integral ceramic construction: Each *Printed Electronic Circuit* is an integral assembly of "Hi-Kap" capacitors and resistors closely bonded to a steatite ceramic plate and mutually connected by means of metallic silver paths "printed" on the base plate. All leads are always the same length, each plate is an exact duplicate of the original or "master".

This outstanding new hearing aid development, illustrated above, was the product of close cooperation between Centralab and Beltone engineers. Working with your engineers, Centralab may be able to fit its *Printed Electronic Circuit* to your specific needs. Write for complete information, or get in touch with your nearest Centralab Representative.

LOOK TO **Centralab** IN 1948!

CRL

Division of GLOBE-UNION INC., Milwaukee

ELECTRONICS — *August, 1948*

21

Fig. 12. Centralab Printed Electronic Circuit/Beltone hearing aid. (*Electronics*, Vol. 21, No. 8, p. 21, Aug. 1948)

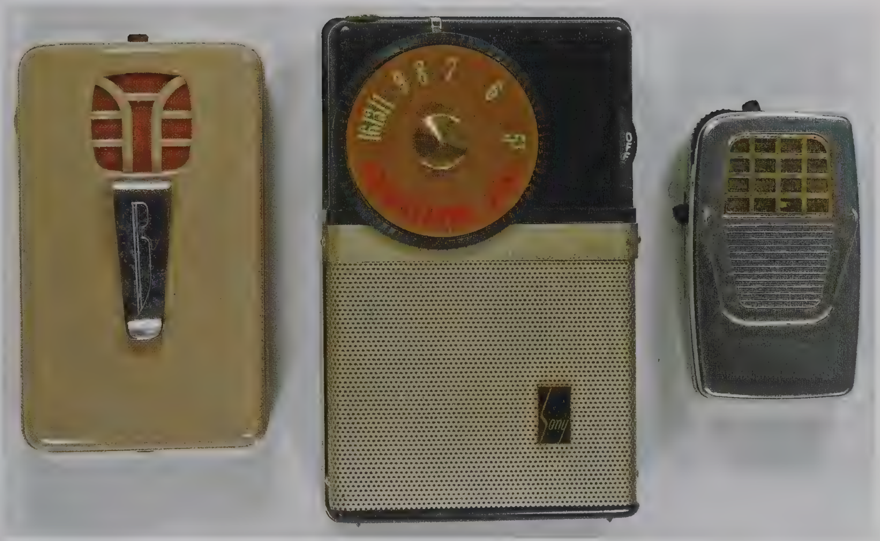


Fig. 13. Size comparison Beltone 3-tube hearing aid 1948, Sony TR-63 transistor radio 1957, Beltone 5-transistor hearing aid 1956. (Author)

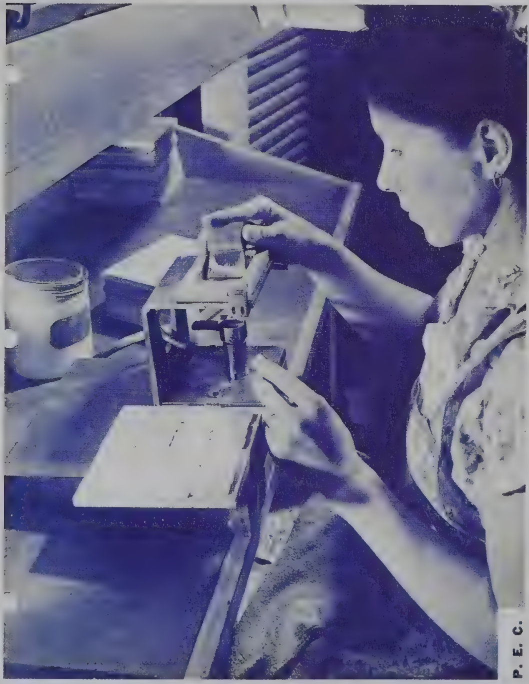


Fig. 14 Manual PEC screen printing process. (Centralab Salesman's Binder, ca. 1954)

Fig. 15.[50] A technical discussion of new ceramic dielectric materials for capacitor applications, distinct from porcelains and steatite, was presented by Centralab.[51]

The number of PEC designs and applications continued to expand through the late 1940s and early 1950s in step with the burgeoning consumer demand for televisions, radios, and other technical applications. A Centralab technical bulletin promoted the many potential PEC applications and depicted the PEC production processes. Perhaps the most interesting step is that, unlike the conductors and resistors that were screen printed on the insulating base plate, capacitors were added separately by sweat soldering onto conductive printed pads on the substrate.[52] The rationale for the separate addition of capacitors revolves around ceramic properties. The dielectric constant of the base plate made of steatite is not very high for capacitor applications. While ceramics that have a high dielectric constant, such as barium titanate, could be used, the capacitive coupling between closely spaced components and conductors becomes a potential problem. Accordingly, the individual capacitors are made with a high dielectric material for later attachment to the lower dielectric base plate to solve both problems.[53] Many designs were customized to specific manufacturer applications with manufacturer-assigned part numbers. While this customization allowed Centralab to provide unique products, this degree of customization would later prove to be the source of consternation among service professionals and restoration enthusiasts.

Breaking a near quarter-century hiatus, Centralab introduced an "active" electronic device under their own name, circa 1951, christened the AMPEC. The AMPEC Model 201 was a three-tube amplifier circuit built on a PEC ceramic substrate (Fig. 16); a schematic diagram is shown in Fig. 17. Like the single-tube Model 100 Tone Amplifier of 1926, additional components had to be added to complete the AMPEC, including not only vacuum tubes but also a volume control, output transformer, and reproducer. A typical frequency response curve for the AMPEC-200/201 is shown in Fig. 18.[54] The Model 201 included three Raytheon subminiature tubes, one CK525AX and two CK512AX, while the Model 200 did not. The ceramic substrate was coated

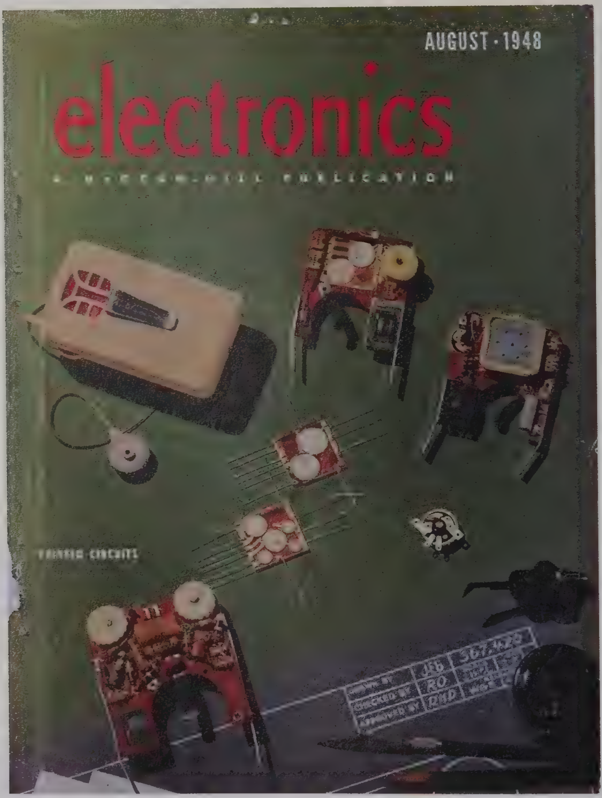
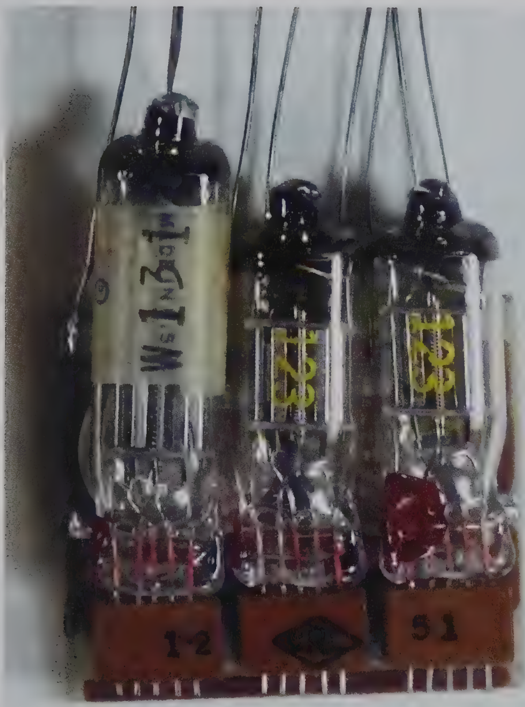


Fig. 15. Centralab Printed Electronic Circuit/Beltone hearing aid cover illustration. (*Electronics*, Vol. 21, No. 8, Aug. 1948)

with phenolic resin and a high-temperature wax to seal the circuits. The AMPEC 2 was supplemented to include two versions of the Model 3, PC202/203 and PC204/205 by 1952. The PC204/205 was smaller and incorporated a tone switch circuit. PC202/203 employed one



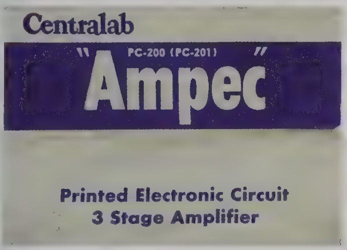


Fig. 16. Centralab AMPEC 201 three-tube amplifier. (Author)

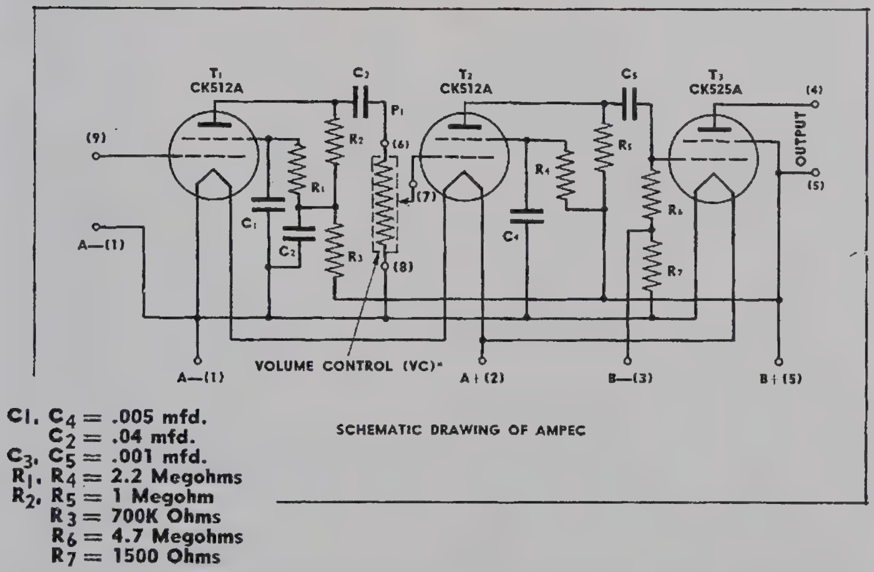


Fig. 17. Centralab AMPEC 201 schematic. (Centralab *AMPEC Instruction Sheet*, Centralab Form 42-142, ca. 1951)

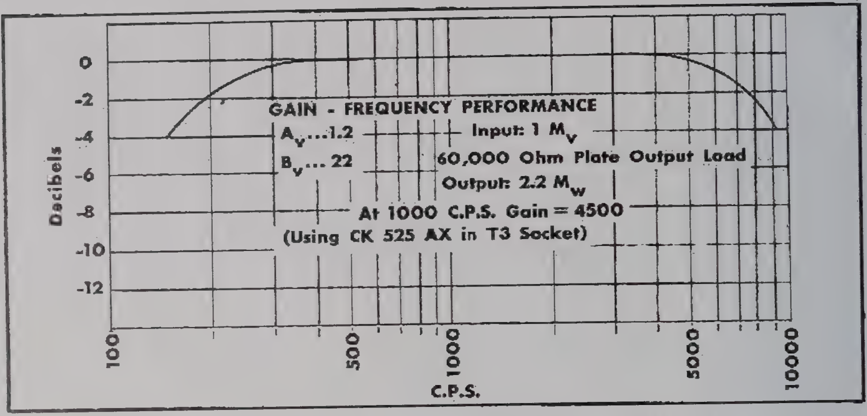
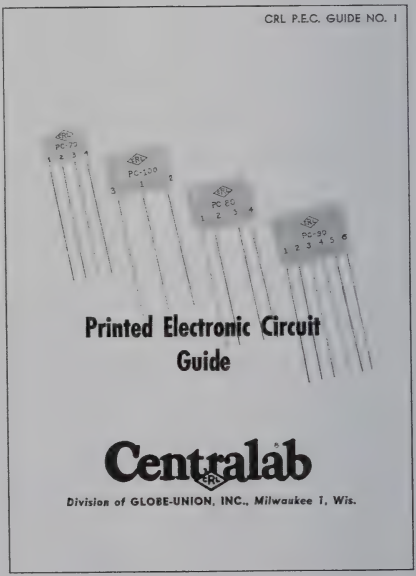


Fig. 18. Centralab AMPEC 201 frequency response curve. (Centralab *AMPEC Instruction Sheet*, Centralab Form 42-142, ca. 1951)

Raytheon CK525AX and two CK512AX tubes. PC204/205 used one CK547DX and two CK538DX when operating in the zero bias output stage or one CK-548DX and two CK538DX tubes when operating in a grid output stage. The model numbers 203 and 205 were supplied with the requisite Raytheon subminiature tubes, while 202 and 204 were not.[55] Pricing for the various configurations ranged from $15.00 for the 200 without tubes to $32.00 for either the 203 or 205 with tubes.[56]

The PEC proved so successful, a dedicated 5½ × 7⅝ 14-page catalog of PEC designs made its first appearance in 1951 (Fig. 19). By that time, 19 part numbers/designs were identified for applications to 69 different radio/TV manufacturers. Some 15,000,000 PECs were reportedly in use.[57] By the time *PEC Guide* 2 was published in 1953, over 25,000,000 units had been produced. This volume contained a "simple series of tests" using a VOM, a 60-cycle capacitor bridge, and PEC component information for troubleshooting and identification of PEC-specific failures.[58] A complete replacement of the PEC was often necessary, particularly when the failed component could not be isolated from the embedded circuit.


CRL P.E.C. GUIDE NO. 1

Printed Electronic Circuit Guide

Centralab

Division of GLOBE-UNION, INC., Milwaukee 1, Wis.

Fig. 19. Centralab *Printed Electronic Circuit Guide* No. 1, 1951. (Author)

As printed circuits became a generic industry term, the PEC could easily be confused with the ubiquitous printed circuit board. At some point around 1955, the definition of PEC changed from *Printed* Electronic Circuit to *Packaged* Electronic Circuit between the 1954 and 1956 editions of the *PEC Guide*.[59] The PEC Guides would continue through at least eight editions up to 1965, being published roughly every other year. PEC offerings grew to 210 standard designs for 188 manufacturers in the 18-page 8½ × 11 *PEC Guide* No. 8, excluding custom OEM designs.[60]

The PEC was widely used, and by 1959, 100,000,000 PECs had been produced. The milestone was commemorated by donation of the part, a PEC-157 audio detector Couplate, to the Smithsonian Institution. The event was memorialized with the production of a commemorative portfolio that included an encapsulated replica part, as shown in Fig. 20.[61] The corresponding schematic and component values of the PEC-157 are shown in Fig. 21.[62]

While the PEC reduced size and OEM connection count, it did not significantly address the number of required internal component connections or allow for the incorporation of integrated active electronics directly applied to the insulating substrate. In addition to radio/television/hearing aid applications, the technology would eventually migrate into more consumer and industrial applications. Many examples of new old stock (NOS) PEC devices are still available on internet sales sites.

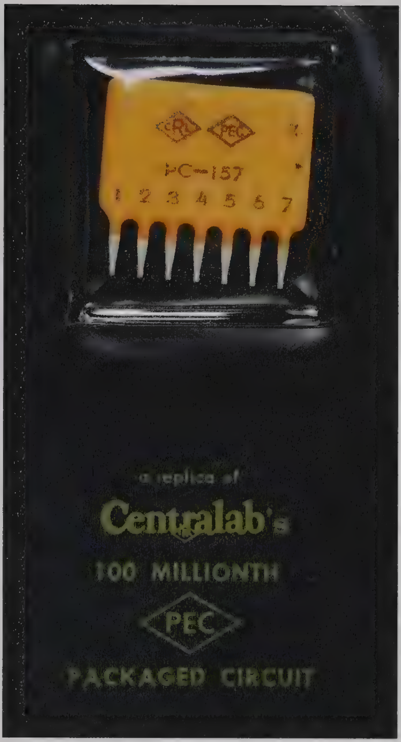
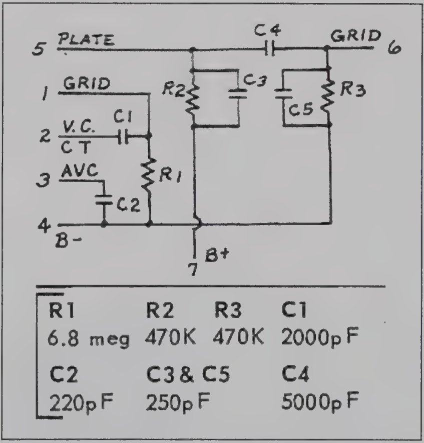


Fig. 20. Presentation replica of Centralab's 100,000,000 PEC. (Centralab presentation portfolio, ca. 1959, author)



R1	R2	R3	C1
6.8 meg	470K	470K	2000pF
C2	C3 & C5		C4
220pF	250pF		5000pF

Fig. 21. PEC-157 schematic and component values. (Centralab *PEC Guide* No. 8, Centralab Division of Globe-Union, Inc., 1965)

Jack St. Clair Kilby

While growth of the PEC line drove the expansion of staffing, the year 1947 was notable at Centralab for one seemingly routine hiring decision. Jack Kilby, a 23-year-old electrical engineer, who freshly graduated from the University of Illinois, was added to the engineering staff.[63] A contemporary photo shows a much younger man than is often seen (Fig. 22).[64] Although he had contacted several potential employers, only three responded by offering on-campus interviews: Collins Radio, a group from Bell Labs, and the Centralab Division of Globe Union. Collins did not pursue making a job offer. Kilby found the Bell Labs activities uninspiring and discontinued discussions with them. He found the Centralab activities to be unusual and challenging. Fortunately, Centralab was the only prospective employer to make a job offer. Upon graduation, Kilby was hired to investigate printing and substrates for PEC applications at Centralab. As a key part of this activity, miniaturization of components and circuitry were givens.[65] While Centralab documentation connecting Kilby with specific PEC designs does not appear to exist, his earliest, as well as continuing assignments, were application specific, including miniaturization of hearing aid amplifiers and television resistor-capacitor networks.[66] Another of his early assignments was to improve the reliability of the resistors incorporated into the various PEC products. The resistors consisted of small carbon deposits screened onto the ceramic substrate. Unfortunately, the size of a given deposit was not reproducible resulting in unpredictable resistances. His solution was to use an otherwise unpopular dental sandblaster to assure that each carbon deposit was precisely the same for a given resistance.[67]

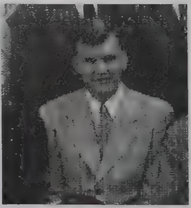


Fig. 22. Jack S. Kilby, ca. 1947. (Ramenofsky, C. K., ed., *The Illio*, Vol. 54, p. 436, University of Illinois, Urbana, Ill, 1947)

His work at Centralab appears to have been going well. By June 27, 1948, he would marry his college sweetheart, Barbara Annegers, in Galesburg, IL. As is the case with many newlyweds, Jack and Barbara began a family with two daughters; an infant son, Jack Jr., was tragically lost to SIDS (Sudden Infant Death Syndrome).[68] By 1953 the couple would build a two-story, three-bedroom house on East Dean Road in the Milwaukee suburb of Fox Point that the family occupied until they departed from the area. Their location proved convenient for family outings to nearby Doctors Park and occasional swims in Lake Michigan "if the water temperature was at all acceptable, which it often wasn't." Jack also recollected that although the nearby Bayshore Mall had recently opened, his shopping choice was a Schuster's Department Store, located on Milwaukee's Third Street.[69] By most measures, Jack and his family were happy.

Jack Kilby would achieve several important milestones during 1950. Along with Alfred S. Khouri, he would co-author his first patent application, submitted on February 27, 1950, for a "Network Having Distributed Capacitance." It would be issued as U.S. Patent 2,637,777 on May 5, 1953. By the spring of 1950, Kilby would also complete his master's degree in electrical engineering through correspondence classes at the University of Wisconsin-Madison. "Design of a Printed Circuit for a Television IF Amplifier" was the title and topic of his thesis and an acknowledged extension of his employment. His thesis consists of a consideration of design factors followed by detailed amplifier construction information. A copy of the final circuit diagram is shown in Fig. 23. Note that he had chosen seven-pin 6AU6 tubes for this design based on performance and cost. By extension, much information in the construction section discusses Centralab production processes. Fig. 24 depicts the three-tube, single-substrate design. An example of the finished product, less coils, shown in Fig. 25, was one of several artifacts obtained from the Kilby estate. By 1952, Centralab was selling an integrated RLC network and tube socket for television applications.[70] Unlike the hearing aid PEC, this unit was designed for television applications with more demanding performance requirements and where size and power consumption are less challenging.

Additional estate artifacts of Kilby's PEC work are illustrated in the following series of illustrations. Although

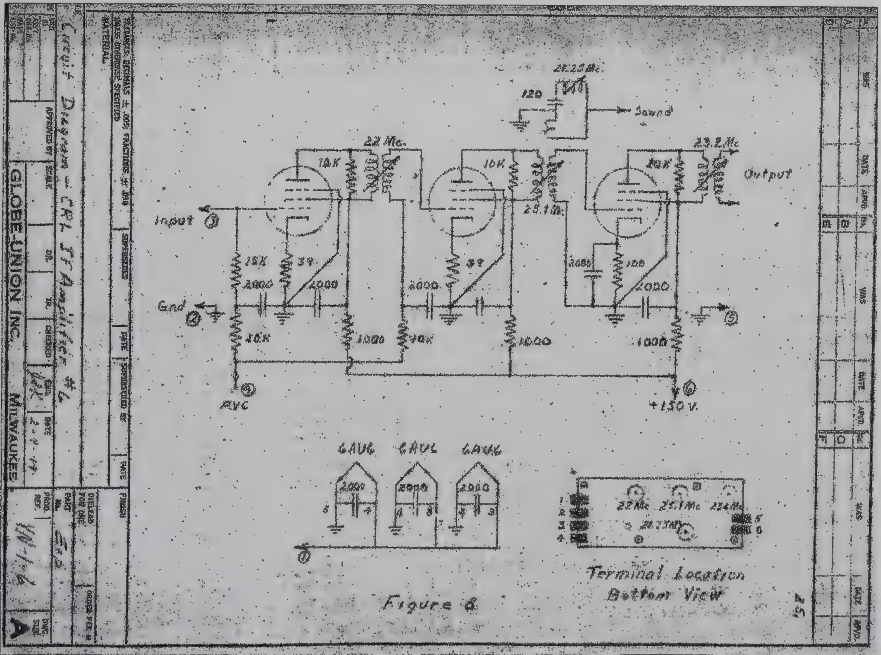


Fig. 23. Circuit diagram for a three-tube television IF amplifier designed by Jack Kilby. (Jack Kilby, Master of Science Thesis, University of Wisconsin-Madison Archives, 1950)

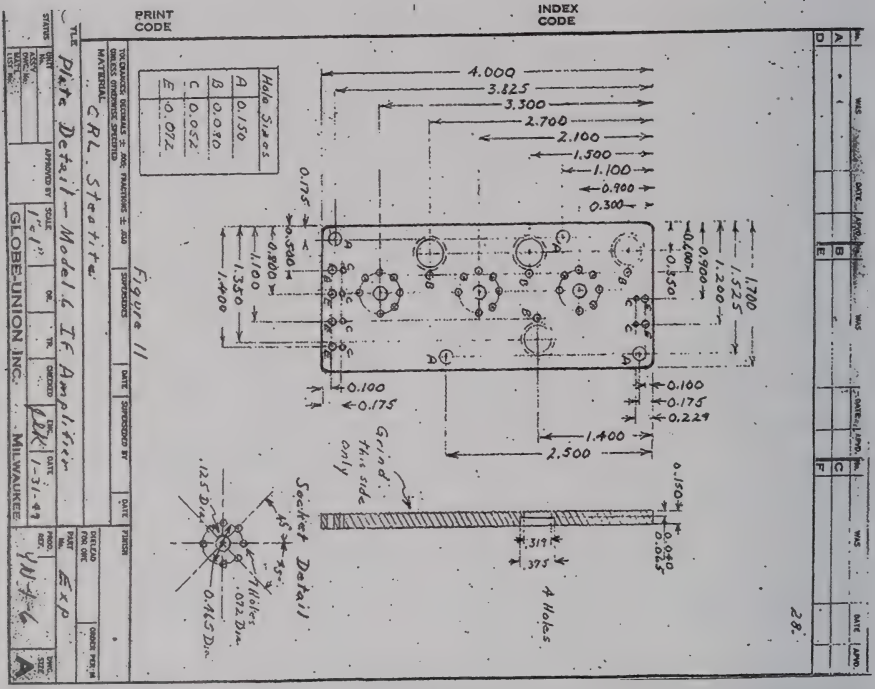


Fig. 24. Engineering drawing for three-tube television IF amplifier substrate by Jack Kilby. (Jack Kilby, "Design of a Printed Circuit for a Television IF Amplifier," M.S. Thesis, Univ. of Wisconsin-Madison Archives, 1950)

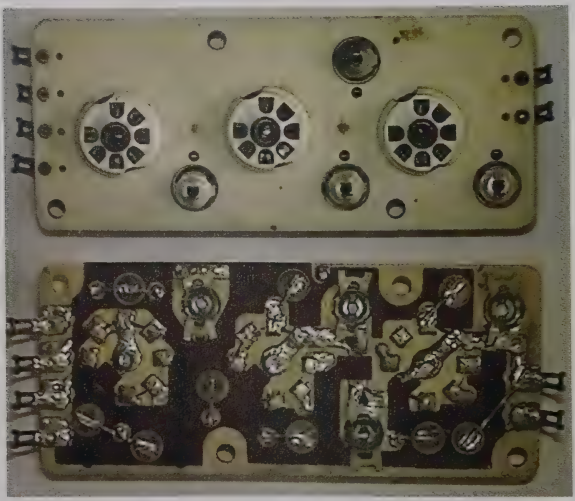


Fig. 25. Completed three-tube television IF amplifier substrate, less tubes and coils. (Author)

their specific functions or applications are undocumented and somewhat indeterminate, they represent artifacts that Jack Kilby thought were worth preserving from his tenure at Centralab. A second device shown in Fig. 26 consists of a seven-pin Bakelite socket attached to a ceramic tube. Close examination reveals several small attached capacitors, printed resistors, and possibly two very thin coils wound around the tube. Fig. 27 shows a fully assembled and coated one-tube PEC using a seven-pin ceramic miniature tube socket. It is interesting to note that the CRL trademark and a hand-written "2" designation are apparent. This device incorporates what appears to be an adjustable tuning feature opposite the tube socket, and seems to be designed for use in a "plug-in" assembly. Only the device of Fig. 27 is likely plug-in.

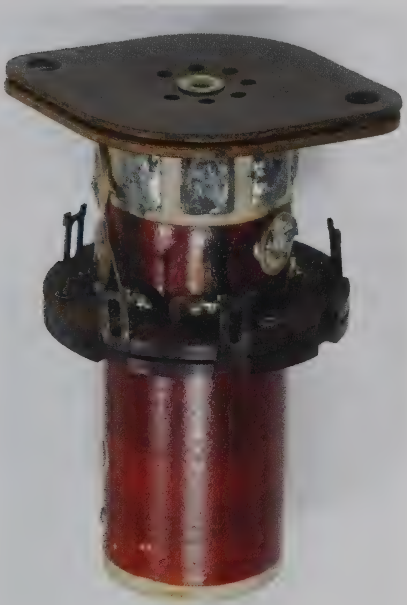


Fig. 26. One-tube prototype attached to a ceramic cylinder with resistors, capacitors, and coils. (Author)

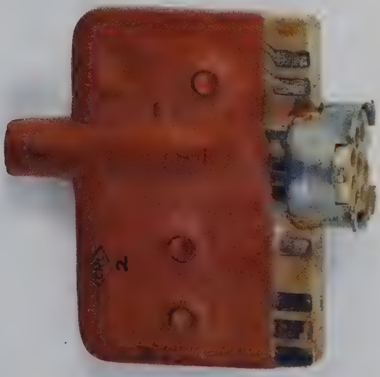


Fig. 27. Fully assembled and coated one-tube PEC prototype, CRL 2, possibly a "plug-in" circuit. (Author)

While the PEC business was flourishing, limitations of the design were surfacing. By 1956, it was observed that "the largest volume in the ceramic printed circuit field has been in more or less standard components" (resistors and capacitors). Limitations included a high shrinkage factor of the ceramic, making dimensional consistency and practical size an issue. In addition, the molding process was inherently costly.[71] Finally, a certain amount of hand assembly was still required when capacitors were incorporated into the PEC. These thoughts, along with his experience, must have weighed on Jack Kilby's mind.

Kilby and the Transistor

In the closing year of WWII, Western Electric/Bell Labs seriously considered the direction of their post-war basic research programs. A conscious decision was made to focus one area of investigation on semiconductor materials for "the development of completely new and improved components." The efforts of the Bell team paid off on December 1, 1947, when a small power gain was observed in a point-contact with a germanium crystal that exhibited the "transistor effect." By December 23, 1947, a speech-amplifying device having an 18-fold power gain was demonstrated. On December 24, the device was operated as an oscillator, definite proof of a power gain. Time was required to understand the theory, practice, and potential of this novel solid-state device and make appropriate patent applications. Over the period of June 17–30, a series of disclosures were made including submission of three letters to the *Physical Review* (published on July 15, 1948) followed by demonstration to the press at Bell Labs, which generated little publicity. The transistor was the featured cover story in the September 1948 issue of *Electronics* magazine and was predicted to have a far-reaching impact on the field.[72]

Jack Kilby was diligent in keeping current with developments in the electronic field and found growing interest, along with his superiors, in the newly announced transistor. This interest led to several key developments. An undated 15-page report, *Transistors—Their Manufacture and Use*, by J. S. Kilby was attached to an internal memo to the Centralab/Globe-Union executive committee dated August 27, 1951. Following a single paragraph of transistor theory, Kilby launched into a discussion of the germanium point-contact, grown junction, and fused junction transistor designs, commenting that the junction design was "destined to achieve the widest use of the three or obsolete the others entirely." He also noted that silicon and lead sulfide were potential alternative base materials and speculated that ceramic materials such as reduced barium titanate may be useful. Barium titanate was a material that Centralab already had experience in processing for dielectric substrates associated with Centralab's PECs and capacitors. Whether Kilby was appealing to the executives with a material they already knew or whether he truly believed in its semiconductor potential is unknown. What followed was a discussion of potential manufacturing processes, although Kilby noted that "No detailed information has been released on the methods actually used in transistor manufacture." He outlined eight major steps in the process from purification of raw material through performance testing. While knowledge of two different germanium preparation processes by Eagle-Pitcher Co. and du Pont were known from the wartime production of germanium diodes for radar sets, some process modifications were likely needed to achieve contact transistor performance, including the use of doping agents and processes. It was also noted that definite details of the junction transistor process had not been released. Kilby went on to discuss the packaging of the transistor: wax-filled brass cases for point-contact transistors or a dipped plastic coating such as Durez for junction transistors. Clearly, Jack had examined, if not attempted to reverse engineer, some of the earliest transistors available. The report concluded with a discussion of potential applications. He noted the need for unique circuit designs, observing that the transistor was not simply a plug-in replacement for vacuum tubes. He suggested that the transition to transistors would be a gradual process likely extending over ten to twenty years. He also noted that transistors had not been designed into any mass-produced device currently on the market. Kilby considered that once performance was improved, applications in computers, telephone amplifiers, military applications, and hearing aids would proliferate at any price. Additionally, if transistor costs were reduced to that of vacuum tubes, approximately 150 million transistors would be required for use in 10 million radios and 5 million televisions per year, not including the replacement market. Kilby concluded: "This, of course, is in the far distant future."[73] Fifty years later, the original copy of this report was donated to the Smithsonian Institution for posterity.[74]

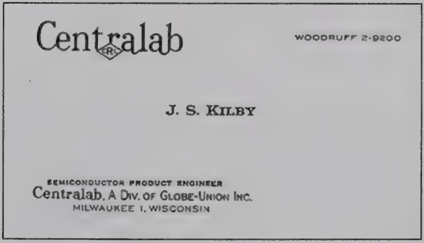
The cover memo by J. F. Harper expanded on Kilby's report stating:

> "This development is most complicated and we estimated that it will require considerable investigation beyond what has been done to date in both new materials (we have several ideas) and new methods. We believe it will require two men with somewhat specialized knowledge, some special equipment, and a matter of one to two years at an estimated cost of $35,000 to $50,000 to develop this product. Manufacturing equipment and costs can only be established after the development is well along."[75]

Shortly thereafter, Jack was assigned to attend a Bell Laboratories workshop on the recently discovered transistor in early 1952 along with one of his superiors, Bob Wolff. This would prove to be an intensive course on how to make point-contact and grown junction germanium transistors, and included a visit to Western Electric's transistor production facility. "Tuition" was $25,000 to license the Bell transistor technology. The fee subsequently could be applied as royalty payments if the participant sold any transistors. Of 35 participating companies, it is noteworthy that one little-known company, Texas Instruments, was also represented.[76] Upon returning to Milwaukee, Kilby was assigned to lead a three-man team to establish transistor production processes and develop transistorized Centralab products.[77]

The complete transistor process was shown at the 1952 International Electrical Engineering show by Western Electric.[78] However, Centralab's transistor project, under Kilby's direction, would not commence until the fall of 1952. His business card from his transistor activities is shown in Fig. 28.

While undertaking to build a suitable development laboratory, Kilby continued to examine the developing transistor field, preparing an updated report dated September 24, 1953.[79] Four major topics were discussed: Transistor State-of-the-Art design and use, Industry Activity, Centralab Team Progress to Date, and Future Centralab Development Directions. What follows are excerpts



Centralab CRL

WOODRUFF 2-9200

J. S. KILBY

SEMICONDUCTOR PRODUCT ENGINEER
Centralab, A Div. of Globe-Union Inc.
MILWAUKEE 1, WISCONSIN

Fig. 28. Jack Kilby's transistor engineer business card, ca. 1953. (Author)

from this report. The State-of-the-Art section noted the development of the grown junction transistor at Bell Labs and the discovery of the fused junction process at General Electric. He noted that Raytheon was producing fused junction transistors in large quantities and that GE and RCA would soon offer their own products. He noted that silicon transistors offered better electrical and thermal properties compared to germanium, but that it was "extremely difficult to fabricate." His final comments in this section noted that transistors "could be expected to last forever, if their housing can adequately protect them from moisture and shock," noting the inconsistent performance reported by users of Raytheon devices. Zenith reported the units to be moisture sensitive and useless for hearing aids, while Beltone reported little trouble with over 100,000 units in their hearing aids. Kilby closed by noting that more than half of the dozen or so Raytheon units tested at Centralab were humidity sensitive and should be hermetically sealed.

In discussing the Industry Activity Section, Kilby summarized the production activities of transistor developers/manufacturers. Twelve companies were discussed, but only five appeared to have substantial information, which has been abstracted in Table 1. He also noted that an additional 17 companies that had received licenses from Bell Labs had made no announcement of activities to date. Kilby concludes this section by noting that transistor prices were likely to come down in the coming months. GE had announced pricing $2 less than Raytheon. The industry was targeting transistor prices competitive with that of vacuum tubes within the year, or about $1.00–$1.65 for subminiature tubes.

In the third section, the Centralab team activities were addressed. Noting that the fused junction design had occupied the majority of their development time, he reported that the initial process

Table 1. Summary of competitive transistor manufacturers 1953, compiled by Jack Kilby. (From* Transistor Development Report*, J. Kilby to R. L. Wolff, Sept. 24, 1953)

COMPANY	TRANSISTOR TYPE	UNIT PRICE	ESTIMATED 1954 VOLUME
Raytheon	Junction	$8.50	Million?
	Point Contact	---	---
RCA	Junction	$9–15	
	Point Contact	$12–15	
GE	Junction	$6.75	3 Million
Western Electric	Junction	---	12 Million?
	Point Contact	---	
Germanium Products	Junction	$11.50	3 Million?

stages were performing satisfactorily, but the assembly processes had caused the most problems, observing that the associated equipment was rather crude. Troublesome processes included fusion of small indium dots on the germanium surface, assembling the unit into a mount, attaching leads, and sealing. With all of this in mind, Kilby noted that "The best of the transistors which we have prepared are quite comparable to those now commercially available." This optimistic statement was tempered by noting that "There are still factors present which cause great variations between units…" He reported a tentative design that was significantly smaller than that of current commercial devices and would be capable of insertion into an insulating base plate, such as steatite, and would not require a socket. It would also potentially eliminate the purchased cases that were "relatively expensive."

The final section of his report addressed future Centralab direction and needs. Kilby outlined three potential directions. The first was to compete with the major companies with large quantities of a broad range of transistor products. He noted the need for a team of 20–40 dedicated engineers, additional large amounts of mechanical and industrial engineering time, and production costs of several million dollars. He acknowledged that this scenario was mentioned for completeness. The second option consisted of singling out a particular type of unit and then selling strictly at a low price. He noted that automated assembly would be necessary. Based on a target of one million transistors per year, a six- to eight-engineer team working for about one year and $200,000 ($70,000 metallurgical process equipment; $100,000 alloy and assembly; $30,000 test equipment) would be needed. His third option included expanding the transistor group to five to six engineers at a cost of less than $60,000 for a year but additional equipment still at $200,000 to achieve one million units a year. Their activities would specifically target perfecting transistors that would be adapted to printed circuits, such as those used in hearing aids. Kilby's fourth, and final option was to continue the current development program. He noted, "This might allow us to keep up with the new developments in the field for a time, but is unlikely to result in production." He reported a monthly expense of approximately $2,500 and a cumulative cost through July 31, 1953, of $77,340, which included the $25,000 Bell Labs fee and $30,000 for equipment.

By the end of 1953, a transistor fabrication laboratory was nearing completion. In addition to the completed workspace and utilities, all major equipment had been installed, including a reduction furnace (built by Hevi-Duty), a zone refiner, and a zone crystal grower (designed and built by Globe-Union for the preparation of purified germanium). Also installed was a Crane Lapmaster for sizing wafers, "crude" assembly fixtures for fused junction transistors, and a dry box for final sealing.[80] Unfortunately, the only extant copy of this report is missing page(s) describing the equipment for intermediate process stages 4–7, which would detail more of the junction preparation and fusion equipment and processes. Apparently, the additional equipment was designed and built by the Centralab team, and the omission of further detail was perhaps for proprietary reasons.[81]

By May 5, 1954, another *Transistor Progress Report* was issued by Jack Kilby.[82] This report followed the same format as the 1953 *Annual Report.* In his State of Transistor Design, Kilby noted that silicon junction transistors had been made by several companies, but were not currently commercially available, commenting that they had "poorer performance and a higher cost." In his discussion of industry activity, the hearing aid continued to be the only marketed product that used significant quantities of transistors. He observed that significant efforts to transistorize both civilian and military computers were being made. Finally, it was reported that Raytheon had lowered their price to $5.85 for premium grade conventional transistors, supplying most of the hearing aid market.

Reporting on current Centralab activities, work was focused on the fused junction transistor and the development of the new mounting discussed in the previous report. He elaborated on the latter noting "The basic feature is a molded plastic part which holds the leads securely and acts as a jig to position the wafer for soldering." A rough sketch was included with the report and described as "JSK-9, Model 1, Transistor Assembly Drawing, March 31, 1954." This unit is then dropped into a recess provided in the steatite printed circuit plate, a cover is welded over the top, and the leads soldered into the bottom of the plate, providing a hermetic seal. While those units that had been assembled proved to be "quite satisfactory," Kilby went on to enumerate several improvements needed before production. In addition, he raised the issue of patent position, as the fused junction transistor was originally developed by GE. He then provided a rough cost estimate for small-scale production of transistors at Centralab. Although a new technology, the throughput yields are somewhat alarming. Starting with a batch of 2,000 wafers/day, the final yield of premium grade product was expected to be 318 units, or almost 16% yield! Second-quality units were expected to be about the same. The premium units were valued at $5.85 a piece, while the seconds were valued at $2.00 each. This would produce a daily value of $2,500. Based on a detailed evaluation of labor, equipment, and materials costs, Kilby estimated the daily expense to be about $600/day. Not included in this calculation was the amortization of development and tooling. It was noted that as of February 28, 1954, the total development cost was $90,585, which included the original license fee. Monthly expenses of $3,000 were reported.

Several artifacts from the Kilby estate would appear to be related to this product. The first items appear to be manufacturing prototypes consisting of a metallic substrate in which ten replicate units were stamped. Fig. 29 shows a strip containing a molded plastic container and four metal arms and a corresponding strip that exhibited devices within the container and the attachment of one metal arm on each top. Closeup examples

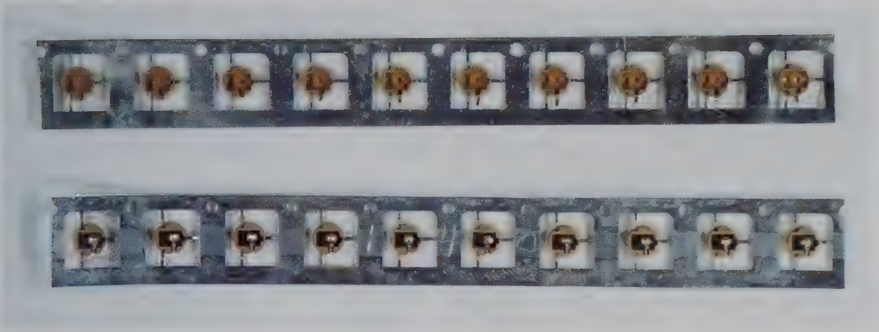


Fig. 29. Prototype Centralab transistor assembly strips in-process, above: empty holders, below: transistor wafers with fused connection. (Author)

of both strips are shown in Fig. 30, which illustrates a dielectric material with an empty rectangular pocket and two through-holes subsequently filled by a fused junction transistor in each pocket, appearing as a dark wafer filling the pocket along with a solder joint at the top. It would appear that the final steps in this process would be encapsulation of the device and parting from the metal frame, resulting in a circular unit having three legs. These parts appear to be early CRL transistors in process, per the illustrations in Kilby's U.S. Patent 2,762,001, and Kilby's earlier description of a rectangular plastic carrier for transistor assembly would support this conclusion.[83]

Fig. 31 shows an unusual device that appears to be an assembly of two distinct components. A thicker three-legged device that appears at the "bottom," which seems to be a transistor assembly, is capped with a thinner disc having an additional lead, likely a disk capacitor. This would be consistent with a comment in Kilby's U.S. Patent 2,945,163: "A disc capacitor…is mounted on the cover…of the mounting for such transistor. Such cover is connected to a silvered area… and hence, the lower electrode of the capacitor…is also connected to such area. The other electrode of such capacitor is connected by a ribbon conductor…to an external lead." This would seem to

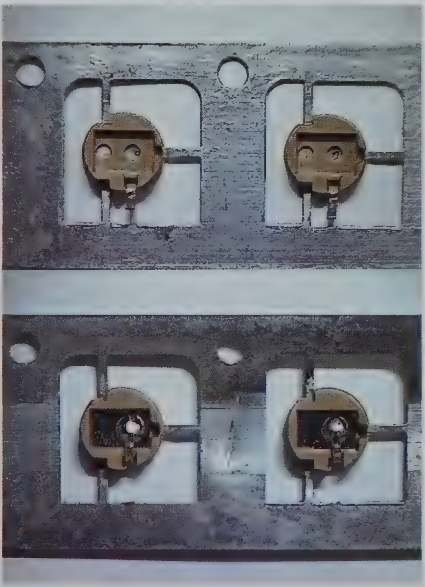


Fig. 30. Close-up of individual transistors, above: empty holder, below: the assembled transistor. (Author)

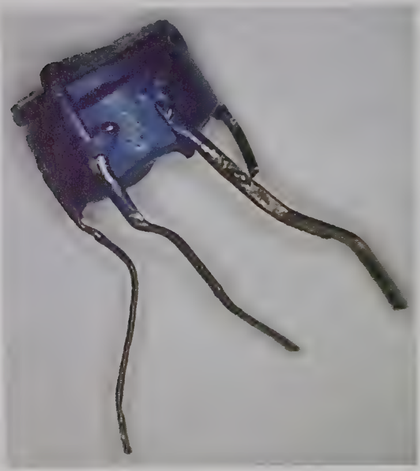


Fig. 31. Prototype epoxy-coated single-transistor amplifier. (Author)

describe the unit in Fig. 31 and explain the fourth lead. The device shown may be a prototype of the TA-6 single-transistor amplifier having been hermetically sealed in blue resin. Details of the TA-6 will be discussed later.

In the fourth and final section of the report regarding future Centralab activities, Kilby noted that they were facing a severe manpower shortage. The current group consisted of four individuals! He estimated that by increasing the group to six members a tentative timetable to reach 500–1,000 units per day by May 1, 1955, could be achieved. In addition to $27,000 for equipment, an expense budget of $5,000–$6,000/month could be expected. He concluded that "preparation for production on any scale would force us to stop most of the development work on the present model, and would not permit any work at all on other types of transistors…this would be a dangerous situation."

The electronics world was about to experience another dramatic change from a small start. By 1954, the Regency transistor radio was offered for sale. Inspired and designed by Texas Instruments to sell their transistors in a consumer device, the transistor radio was modified and produced by I.D.E.A. Shortly after October 18, 1954, the Regency TR-1 was announced for the Christmas season at $49.95.[84] Intended to engage the general public with the advantages and opportunities presented by the new technology, the compact size, low weight, and extended battery life would ignite new consumer demand. With economies of scale, production costs and pricing of transistors were expected to drop significantly. Only hindsight can see the impact and importance of this development.

A draft version of Kilby's annual *Transistor Progress Report* for the 1954 year-end varies from prior formats by focusing exclusively on the Centralab transistor efforts.[85] He reported that approximately 600 fused junction transistors had been delivered to the printed circuit group for circuit development as well as process experience. By March 1954, transistor yields were approximately 10%. After experimentation with varied designs, the final design was chosen which consisted of a molded plastic base to hold leads and served as a soldering jig, as had been previously proposed. It was noted that the transistor could be hermetically sealed into a steatite base plate. By April, samples had been made, but yields were low with highly variable performance. As a result, improved processing equipment was acquired for germanium purification and crystallization. An electrolytic etching process was developed to improve indium penetration into the wafer for a more uniform junction. Additional tools to improve alignment and measurement were also installed. Process changes included an alternate solder composition and soldering individual leads one at a time instead of simultaneous soldering of all leads. By the first week of 1955, quality had improved with a yield of 36% premium transistors and 15% second grades for 160 units processed.

What appears to be an early example of this concept is shown in Fig. 32. The device appears to contain two variable resistors, one with the rotating CRL knob attached. Significantly, there is a recess of approximately 0.25 inch diameter in the center of the base plate. There are three feedthroughs at the bottom of the well. This feature is consistent with the hermetic sealing of the transistor in the ceramic base plate described above. This may be a proof-of-concept device or a very simplified hearing aid prototype. This device bears a strong resemblance to the features described in Kilby et. al. in U.S. Patent 2,883,499 for a resistance trimmer.[86]

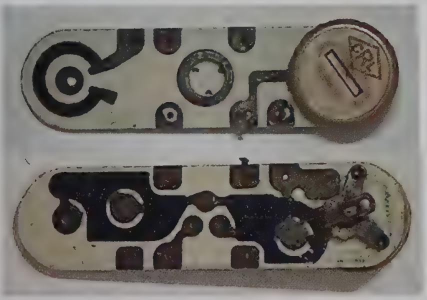


Fig. 32. Early baseplate for hermetically sealing a single transistor. (Author)

Unfortunately for Centralab, while Kilby was able to target production of 2,000 germanium transistors per week (approximately 100,000 transistors/year) in 1955, other competitors were producing significantly greater quantities. Raytheon announced their "Millionth Transistor" on June 23, 1954. General Electric, Motorola, Philco, RCA, Sylvania, Texas Instruments, and Western Electric were all significant semiconductor sources, contributing to a total of 3,500,000 mostly germanium transistors.[87] Relatively high piece costs relegated transistors of the era to military and aerospace applications that required robust, compact, and efficient electronics. Armed forces purchased nearly all 90,000 point-contact transistors produced by Western Electric, although reliability was a major issue. A 1955 report by the military noted that 75% either failed completely or exhibited noncompliant electrical properties.[88]

At this time, a single three-stage printed circuit transistor amplifier was designed and constructed at Centralab. The unit was found to have good gain and frequency response. Kilby went on to note that an alternative to tantalytic capacitors was needed to achieve the best overall size advantage. He went on to discuss an alternative surface barrier capacitor design based on a ceramic substrate. Kilby prepared a separate seven-page report, *Reduced Titanate Capacitors*, containing a theoretical explanation, results of test piece design and evaluation, alternative substrates, and patent review.[89]

The 1954 *Transistor Progress Report* concluded with a discussion of work for the coming year, 1955. Major effort during the first part of the year would be devoted to bringing the Centralab-designed transistor to production and seeking assembly labor savings. He optimistically reported that the transistor development group, consisting of two engineers, a chemist, and a physicist, "is capable of getting the present model of transistor into production on schedule." Kilby did note that the addition of a technician and possibly another engineer may be necessary if the program were to be accelerated. Separately, the group was also expected to develop diodes for computer applications and start their production by year-end. The intent was to provide a "complete package" consisting of transistors and up to six diodes per transistor to the end customer. Given the size of the transistor team, these seem like very ambitious goals.

During this period, Kilby continued to wear two hats: PEC engineer and semiconductor development engineer. One of the fruits of his joint labors is illustrated in Fig. 33. This example, retrieved from a sale of his estate, exhibits a ceramic substrate with an unusual feature: a series of four pockets approximately 0.25 inches in diameter, each having three holes at their bottom and a metallic ring at the top. Perhaps this is an early example of a four-transistor amplifier. These features bear a strong similarity to the device described in his patent with LeRoy E. Dilger entitled: "Component Mounting for Printed Circuits." Originally filed on January 10, 1955, U.S. Patent 2,945,163 was not issued until July 12, 1960. Figures 5–8 of the patent appear to bear common features with this device. As disclosed in the patent "any of the above mounts and seals to fasten a transistor… to an insulating plate."[90]

A final document, apparently from the 1955 period, addresses future transistor development work.[91] A key issue was the wide variety of transistors entering the market compounded by the PNP and NPN configurations. Kilby noted that each type had virtues and limitations. He specifically mentioned the use of grown junction NPN transistors in the Regency radio while General Electric used rate-grown NPNs and Raytheon used junction PNPs for radio applications. Kilby went on to suggest two parallel Centralab development activities: i. Concentrate on diffused junction silicon transistors proposed by Bell Labs; ii. Build up a Centralab circuit development group to translate concepts into PEC packages. He

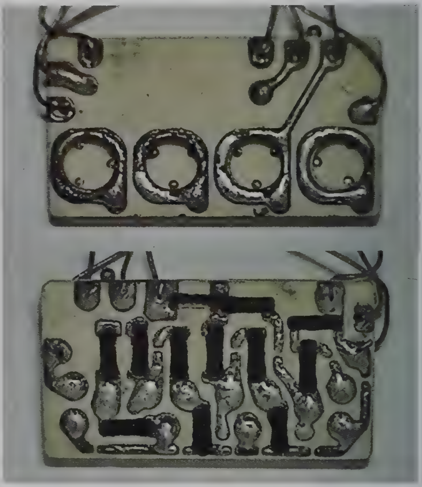


Fig. 33. Early baseplate for hermetically sealing four transistors. (Author)

continued by recommending direct engineering contact with potential customers, rather than through a Sales Department intermediary, and worked to standardize packaging of the electronics. Kilby concluded that the fused junction and the new (Bell) diffused junction transistors will cover most applications encountered by Centralab.

The trail of Centralab transistor progress reports ends here. By 1956, several different transistorized Centralab amplifiers were being produced on a limited basis.[92] Although in direct competition with Raytheon, some of these may have been used in Beltone hearing aids where size, weight, and battery life were all critical features. It would appear that one of the finished products is shown in Fig. 34, which illustrates a finished can in Centralab blue having a part number or code along with the CRL trademark. Based on illustrations and data in general catalog No. 30 as well as the temporary issues of Centralab *Engineering Previews for Packaged Transistor Amplifiers*, the device is likely a TA-6 single-transistor audio amplifier. It is marked CRL 8419459, 748. The schematic for the TA-6 is shown in Fig. 35. The only difference between the TA-6 and TA-7 amps is the deletion of R-3 and lead #3 from the TA-6 circuit. A follow-up series of documents, Centralab *Engineering Preview* (Temporary Issue), EP-75, with undated revisions 1–3, helps to fill in further developments during the 1956 period. The first edition, dated January 26, 1956, introduces the packaged transistor amplifier line. Four devices were presented. The TA-6 was a single-stage audio transistor amplifier having four leads intended to drive an output stage. It consisted of a single transistor, three resistors, and a single capacitor. The TA-7 was a single-stage audio output transistor amplifier, which used similar circuitry to the TA-6 except for the elimination of the third resistor and lead #3. Both were packaged in a cylindrical container 0.250" in diameter and 0.200" tall (excluding leads) and both devices had ribbon leads, 0.005" thick by 0.020" wide and 0.25" long. While the catalog information does not provide complete identification or connection information, the engineering previews

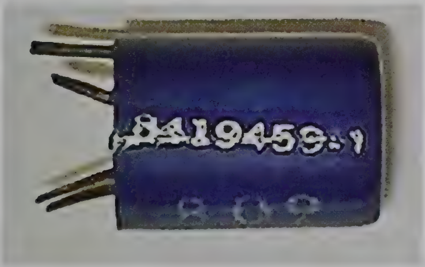


Fig. 34. Centralab single-transistor amplifier TA-6, ca. 1956. (Author)

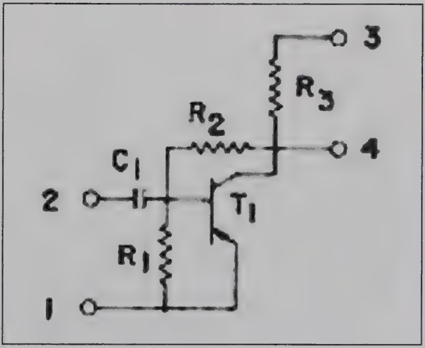


Fig. 35. Centralab single-transistor amplifier TA-6 schematic. (*Centralab* general catalog No. 30, May 1957)

do provide pin-out details, although they too lack resistor and capacitor values. The absence of component values may either be for proprietary reasons or to allow potential customers to specify their own particular circuit values. The other two devices were the TA-10 and TA-11, which contained either a three-transistor or four-transistor audio amplifier in a single package. The TA-10 consisted of two TA-6s driving a TA-7 with associated resistors and capacitors. It offered a gain of 75 dB @ 1 kHz with a frequency response of 250–7000 Hz @ +/-5 dB. Aside from the Engineering Preview documents, it is unclear if the TA-10 was produced in any quantity, as it is absent from the *Centralab* general catalog No. 30. The TA-11, illustrated in Fig. 36, utilized three TA-6s driving a TA-7. Identifying markings are CRL, SA104-001, 614. The TA-11 schematic is shown in Fig. 37. While the TA-11 produced a similar gain to the TA-10, the frequency response covered the range of 250–20,000 Hz @ +/- 5 dB. Physically, the TA-11 epoxy-sealed unit contained seven leads and was slightly larger than the TA-10, measuring 1.175" × 0.665" × 0.250". This was a remarkably small device for its time and a likely candidate for hearing aid applications. Both the TA-10 and TA-11 required additional components to make a complete amplifier including volume control, input and output devices, and a power source. Additional details of these devices are summarized in Table 2.[93]

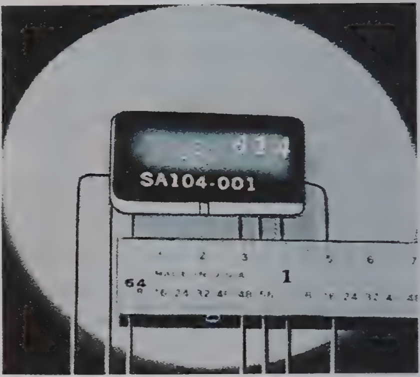


Fig. 36. Centralab four transistor amplifier TA-11. (*Centralab* general catalog No. 30, May 1957)

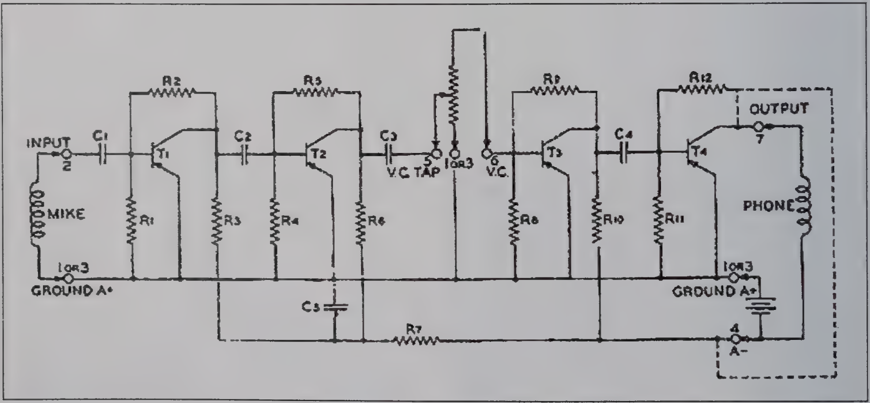


Fig. 37. Centralab four transistor amplifier TA-11 schematic. (*Centralab* general catalog No. 30, May 1957)

The small production facility was marginally profitable, selling small quantities of transistorized amplifiers for hearing aid and other applications. By this time, it became evident that rapid changes were happening in the transistor field. Military applications required the stability of silicon substrates in place of germanium. Also, diffused transistors were proving advantageous. These factors would necessitate expanding the staffing and would require substantial expenditures to remain competitive, which Jack deemed to be beyond Centralab's resources.[94] These early Centralab transistor devices had disappeared by the time general catalog No. 31 appeared ca. 1959.[95]

One of the other fruits of Kilby's efforts was a ruggedized transistor encapsulated in a ceramic body. The basic transistor design was covered by a patent.[96] A device that was originally shipped to the U.S. Naval Research Laboratory in 1957 is shown in Fig. 38, which illustrates the emitter and collector connections of the device.[97]

While some contextual attributions can be made for many of the Kilby artifacts, two devices are somewhat of a mystery at this writing. Both mystery devices would appear to date within a year of 1956. One consists of a canned device having the size and appearance of a TA-6 or TA-7, but unlike the documented amplifiers, the mystery piece features a total of five leads. It is marked CRL 8419459-1, 809, which has not been identified. A second mystery piece, Fig. 39, consists of a rectangular metal-encased device. It too has five leads, but measures 1⅜" × 1¼" × ⅝". It is marked CRL MA202-002, 805, but again, no specific reference material has been found to identify its function or lead connections. An undated Centralab publication, likely ca. 1960, shows a four-transistor amplifier, in a similar case with six leads,

Table 2. Summary of Centralab early transistor amplifier characteristics. (From Centralab **Engineering Preview Packaged Transistor Amplifier EP-75,** ***dated Jan. 26, 1956, and Revisions 1–3)***

TYPE	TA-6	TA-7	TA-10	TA-11
TRANSISTOR COUNT	1	1	3	4
SHAPE	Round	Round	Rectangle	Rectangle
SIZE (inches)	0.280 dia.	0.280 dia.	0.890 L	1.175 L
	0.200 h	0.200 h	0.670 W	0.665 W
			0.250 D	0.250 D
LEADS	4	3	11	7
LEAD TYPE	0.25" Ribbon	0.25" Ribbon	1.5" AWG 26	1.5" AWG 26
GAIN (dB) at 1 kHz	21	26	75	75
INPUT IMPEDANCE (ohms)	1000	500	1000	1000
DESIGN LOAD IMPEDANCE (ohms)	500–1500	1000	1000	1000
SIGNAL TO NOISE RATIO (dB)	<1 mV	<0.5 mV	39	20
OUTPUT POWER (mW)	Drives TA-7	1	1	1
FREQUENCY RANGE (Hz)	250–20,000	250–20,000	250–7000	250–20,000
SUPPLY VOLTAGE (V)	1.3	1.3	1.3	1.3
CURRENT DRAIN (mA)	0.4 – 0.6	1.8 – 2.2	4	3.6 – 4.4

and a completely different numbering system, as in Fig. 40.[98]

More details regarding the semiconductor operations and the state of Centralab can be gleaned from an internal document, *Communique Centralab*, distributed monthly to the Sales and Marketing staff. It was first issued in September 1957, and addressed five areas of concern: Problems Solved, Know Your Products, Personnel, Market Analysis, and Advertising. This first issue contained the announcement that the microminiature TA-12 transistor amplifier was in production. This device contained four transistors and had the same performance as the TA-11, but in one quarter the size. It also mentioned that a special miniaturization editorial regarding the single-stage TA amplifier had been published in the September issue of *Electronics* magazine.[99] Unlike the rectangular TA-11, the TA-12 was encapsulated in a

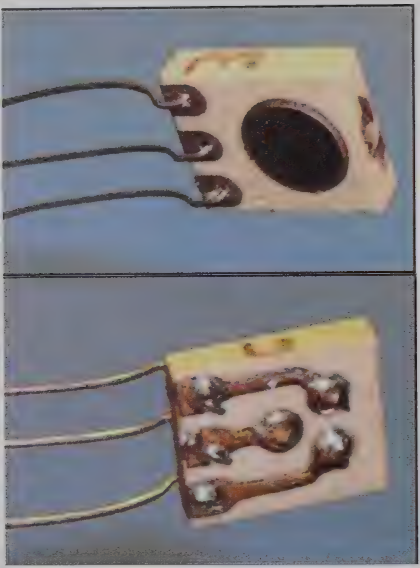


Fig. 38. Centralab ruggedized transistor, 1957. (The Transistor Museum, © 2001–2022 by Jack Ward, Transistormuseum.com.)

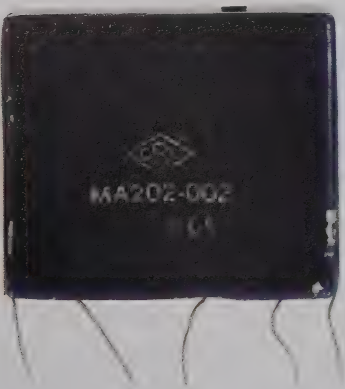


Fig. 39. Centralab Mystery Device. (Author)

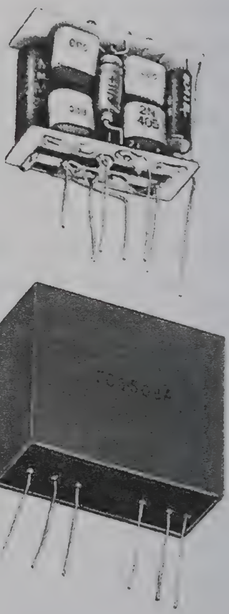


Fig. 40. Centralab four-transistor amplifier container and contents (Centralab *Packaged Transistor Amplifiers*, Centralab Form 42-1018R2, Centralab Electronics Division of Globe-Union, Inc., ca. 1960)

cylindrical package 0.531" in diameter by 0.228" tall, excluding the length of the seven leads. The description and specifications of the TA-12 did not appear until general catalog No. 32.[100]

By November 1957, an announcement appeared that semiconductor production had been transferred from the engineering group to the regular manufacturing division. Semiconductors were no longer a pilot operation at Centralab. Separately, it was noted that the fourth quarter business was a bit soft.[101] A month later, W. S. Parsons stated: "The slowdown in business is now obvious in even the most isolated areas…it seems that the softness will continue into 1958." He followed this observation with "You are not going to find much growth in the old established products of our industry."[102] One bright spot was reached in February 1958, when production of the TA-12 amplifier was steadily rising and capacity would be able to service additional customers shortly. A mention was also made regarding a promotional contest for TA amplifiers, possibly conducted through *CQ* magazine. While apparently still in progress, the promotion had boosted TA sales by some 300%. The counterpoint was the reality described by Parsons: "January is going to be poorest month in past four years. This means it will be your poorest Centralab month."[103] By April, PEC deliveries were proving to be a problem. Most customers were requesting 2-week deliveries when 4–6 week delivery times were normal. They were also requesting smaller volumes of a greater variety of units. Despite this dilemma, Centralab had rehired less than 10% of the workforce laid off between October 1957, and January 1958.[104] The situation appears dire, although the promotion of new products and markets were always highlighted. Here the trail runs cold, as no further issues of the *Communique* have been found. It is known that they were distributed through at least July 1961, as Vol. 4, No. 7.

The year 1957 produced another milestone for the global and U.S. electronics industry. In business for less than 10 years, an obscure Japanese company, Tokyo Telecommunications, also paid the AT&T $25,000 transistor technology license fee. Their representative, company founder Masura Ibuka, was another attendee at the early 1952 Bell Labs transistor workshop. Though not Tokyo Tech's first transistor radio, they introduced the first "pocket-sized" all-transistor radio into the U.S. consumer market, the highly collectible Sony TR-63. The TR-63 was on the U.S. market by Christmas, 1957, with over 100,000 units selling for $39.95.[105] With the clarity of hindsight, the transition of global consumer electronics to Asia had begun.

By March 1958, Jack was rewarded for his achievements with a bonus. His joy was quickly tempered by comments in the accompanying award letter from C. O. Wanvig, Sr., about deteriorating business conditions at Centralab. There were economies to be expected by all employees. The future at Centralab did not look promising and within two months, an announcement was made by R. L. Wolff: "J. S. Kilby is resigning May 15 to take a position as Senior Project Engineer with

Texas Instruments, Inc."[106] By the time of his resignation, Jack had been responsible for ten pending and issued patents that were assigned to Globe-Union.

Prior to his departure to Texas Instruments, Kilby noted that "too many companies (are) producing too many discrete parts at too low prices" and observed that "It was pretty clear that semiconductors were gonna require much bigger investments than Centralab was prepared to make.... That was my basic reason for leaving."[107]

With Centralab in his rearview mirror, Jack Kilby and family began their trip to Texas and his date with history. Unlike the low-cost, high-volume selling philosophy of Centralab, Texas Instruments focused on "higher prices for cutting edge products that people couldn't get by any other means. Higher profits would compensate it for the funds it spent on research. What's more, its discoveries would help the company grow larger by expanding into new markets that its new products created." The Texas Instruments philosophy surely appealed to Jack Kilby. At TI, Kilby had completed the first germanium integrated circuit by October 1958 and filed for patent coverage by February 1959.[108] He would later be responsible for development of the integrated circuit for the first Texas Instruments hand-held calculator, the TI-2500 Datamath, which contained 5,000 transistors on a single chip and was marketed in 1972. By the year 2000, Kilby would receive the Nobel Prize in Physics for his invention of the integrated circuit.[109] Years later, Jack would acknowledge that his work at Centralab provided the foundation for his later inspiration for the integrated circuit.[110] In his own words, Kilby stated that "Centralab was a fortunate choice for me...The company developed thick film hybrid circuits, which were perhaps the first form of miniaturization. In addition, I had an opportunity to see the entire manufacturing process including engineering, sales, and production."[111]

It should be noted, the focus of this discussion is specific to Centralab and Jack Kilby's career there. Pat Haggerty, Willis Adcock, and the teams of individuals at TI as well as Bob Noyce, Jean Horni, and the teams at Fairchild Semiconductor should not be overlooked in the development of silicon semiconductors, the integrated circuit, and the processes and products that we benefit from today. Thorough discussions of these topics can be found in a variety of sources including: H. Queisser, *The Conquest of the Microchip* (1988); J. Zygmont, *Microchip* (2003); E. Keonjian, *Microelectronics* (1963); and F. M Smits, *A History of Engineering and Science in the Bell System: Electronics Technology (1925–1975)* (1985).

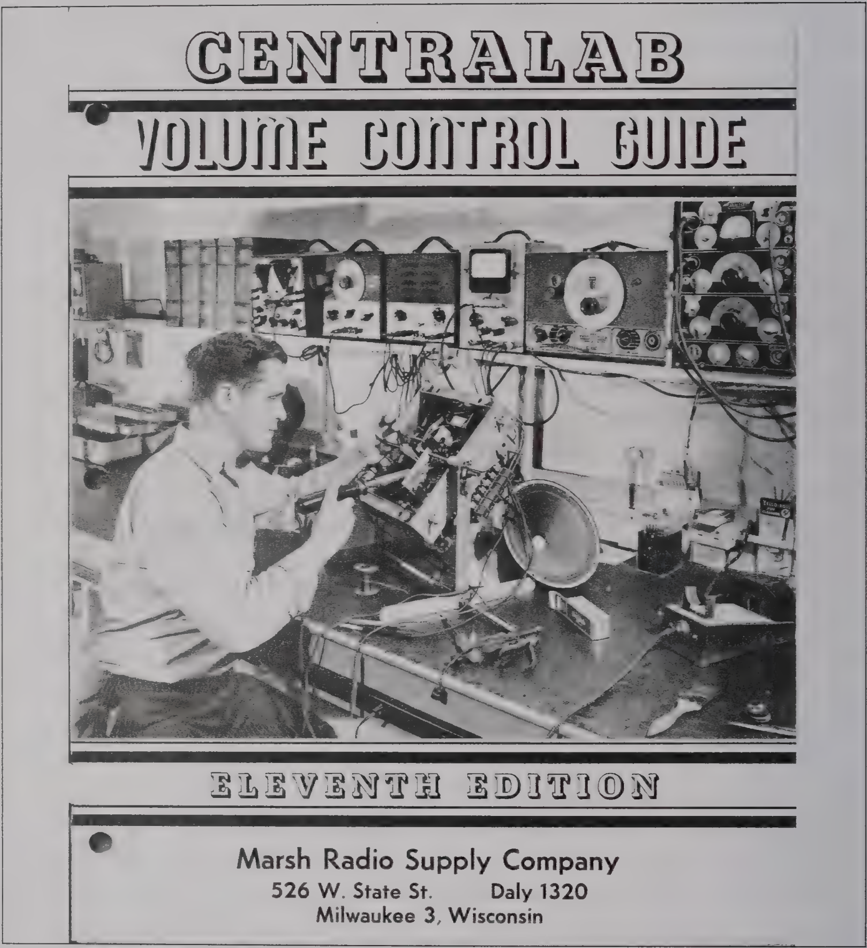
Established Centralab Product Lines

Centralab's pre-war product lines of variable resistors, capacitors, and switches continued to grow as electronics designs, specifications, and processes evolved. No attempt will be made to enumerate all of the various Centralab designs or specifications, while selected products will be highlighted.

Centralab post-war advertising shifted focus to heavier promotion in electronic engineering and radio/television servicing publications. For example, while pre-war Centralab advertising appeared monthly in *QST,* regular advertising was discontinued after 1946 and became opportunistic as relevant new products were introduced. Alternatively, the PEC was heavily promoted in electronic engineering publications such as *Electronics*. Other favored electrical engineering publications included: *Electronic Industries, Electrical Management, FM, Television, IRE Journal, Factory Management*, and *Industrial Equipment News.* Advertisements appeared regularly in publications including *Service, Communications, Electrical Equipment News, Radio Jobbers News, Radio and Television Retailers*, and *Radio Service Dealer.* Amateur/hobbyist publications that continued to contain relevant ads included *Radio-Craft*, *Radio News*, *QST,* and the *Radio Amateur Handbook.*[112] One significant promotional opportunity was realized when Centralab parts were referenced in *Sam's Photofacts* schematics. The first listings for Centralab replacement controls (variable resistors) and capacitors were referenced for television and radio applications in *Photofacts* Folder 93, dated May 1950.[113] This relationship would continue for decades. In addition to subscription publications, Centralab also published a plethora of bulletins, guides, and other documentation, some of which will be discussed below.

The 11th edition of the *Volume Control Guide* resumed the pre-war practice of cross-referencing CRL variable resistance products for replacement applications. Data in this edition contained over 200,000 listings for radios, amplifiers, and record players models manufactured between 1935 and early 1948. The front cover of this edition featured a well-equipped service shop of the era, Erv's Radio Service, located at 1626 W. North Avenue in Milwaukee, shown in Fig. 41.[114] The volume control guides continued to grow with the ever-expanding variety of consumer electronics and manufacturers. *Volume Control Guide* No. 14 was published in 1954 (Fig. 42). Consisting of 300 pages of information and priced at $1.50, it appears to be the final edition of the *Volume Control Guide.*[115] With the growing number of manufacturers, increased product introductions, and the appearance of Centralab replacement parts in *Sam's Photofacts*, the *Volume Control Guide* became burdensome to maintain and redundant to other sources. Subsequently, a much reduced 3¾" × 8½" "pocket-sized" quarterly replacement guide was introduced (Fig. 43), but was directed to only the most recent products. Contents included televisions, radios, and automobile radios. An individual copy cost 20 cents or five issues for $1.[116]

The *Centralab* general catalog No. 25 of 1946 introduced the first group of new post-war resistor and capacitor products. The old Radiohm nomenclature was replaced by a series of corresponding letter designations: Model R (Standard Radiohm), Model M (Midget Radiohm), and Model E (Elf Radiohm). New lines of capacitors based on Centralab's extensive ceramic experience were introduced.



CENTRALAB

VOLUME CONTROL GUIDE

ELEVENTH EDITION

Marsh Radio Supply Company
526 W. State St. Daly 1320
Milwaukee 3, Wisconsin

Fig. 41. Erv's Radio Shop on the cover of Centralab *Volume Control Guide*. (Centralab *Volume Control Guide*, 11th ed., cover, Centralab Division of Globe-Union, Inc., Milwaukee, WI, 1947)

High dielectric constant (HDC) tubular capacitors rated between 0.001–0.01 μF @ 350 VDC, silver mica caps for high-frequency applications rated at 100–2400 pF @ 350 VDC, and transmitting capacitors having silver fired onto ceramic dielectrics rated at 2–200 pF and up to 30 kVDC were described.[117]

General catalog No. 26 of 1948, Fig. 44, is particularly interesting in the collages of various factory photos that were included along with product listings. Notable product changes include the Radiohm Model I, promoted as the "world's smallest commercially produced control." Measuring ⅝" diameter by 15⁄32" deep including terminals, the unit seems large by present-day standards. It was available in resistances of 500 kΩ to 3 MΩ with or without an additional switch for hearing aids and miniature amplifiers. The most notable capacitor introduction employed "completely new" silver and copper conductors permanently bonded to a ceramic disk. This version did not compensate for temperature variation. Different insulating coatings were available including wax, lacquer, or a special phenolic. Capacitance values ranged from 10 pF to 0.01 µF @ 600 VDC. The other new capacitor product was specific for television applications, rated at 500 pF and up to 20 kVDC.[118] Other new products

Centralab
VOLUME CONTROL GUIDE
"INCLUDING RADIO AND TELEVISION REPLACEMENTS"
GUIDE NUMBER FOURTEEN
CENTRALAB VOLUME CONTROL GUIDE NO. 14

Fig. 42. Centralab *Volume Control Guide*, No. 14, 1954. (Author)

Fig. 44. *Centralab* general catalog No. 26, 1948. (Author)

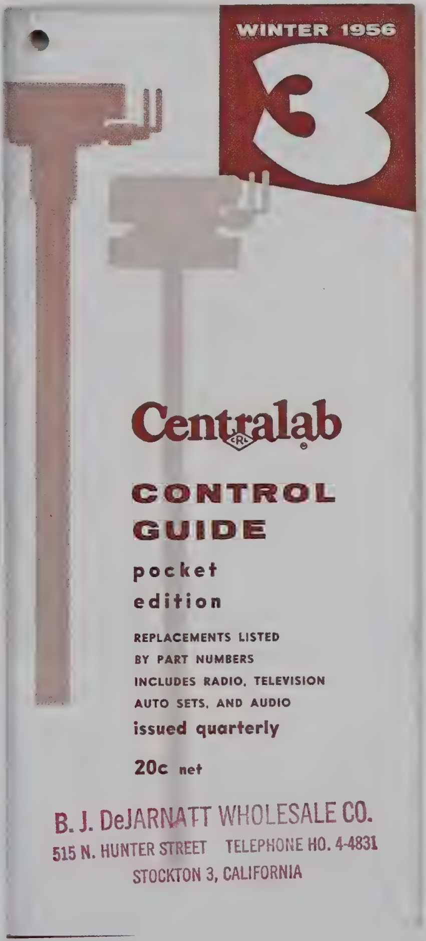

WINTER 1956
3
Centralab
CONTROL GUIDE
pocket edition
REPLACEMENTS LISTED BY PART NUMBERS
INCLUDES RADIO, TELEVISION AUTO SETS, AND AUDIO
issued quarterly
20c net
B. J. DeJARNATT WHOLESALE CO.
515 N. HUNTER STREET TELEPHONE HO. 4-4831
STOCKTON 3, CALIFORNIA

Fig. 43. Centralab *Control Guide*, pocket edition No. 3, Winter, 1956 (Author)

including a "revolutionary" flat multi-contact slide switch for AM/FM applications, lever action switches, Models R (1 W composition or 3 W wirewound), E (direct contact composition ¼ W), and M (composition, ½ W) Radiohms, and ceramic capacitors were introduced in period publications. *Bulletins* 953, 697, 970, and 933 offered additional product details.[119]

Subsequent new editions of the *Centralab* general catalogs appeared in approximately alternating years through the 1950s. Beginning with catalog No. 27, ca. 1950, each featured a different redesigned cover. Fig. 45 illustrates general catalogs 27–30, spanning the approximate period 1951–1957. While the series maintained the 8½ × 11 page size, the page count ranged from 16 to 24 pages. For electronics designers, these modest publications were supplemented by more detailed individual product bulletins. The general catalogs would continue into the 1960s.

About 1951, general catalog No. 27 appeared with a variety of controls, capacitors, and switches designed for television applications. The catchphrase "Safest for Servicing" made its first appearance. The most notable new product was the Blue Shaft control line, which featured a bright blue-colored shaft, Fig. 46. Model B employed a carbon-based resistance element and a phosphor bronze double wipe contactor. Resistances of 500 Ω to 10 MΩ were available and all were rated at ½ W. Models BB and SBB provided twin tandem rotation or concentric shaft controls, respectively. The Add-A-Shaft line, which featured resistance controls that would have the appropriate shaft configuration installed by the service tech, was expanded with additional choices of shaft configurations. Making a first-time appearance were the AMPEC and AUDET PEC products, designed for speech amplification and AC/DC radio output stages, respectively. To address variable television signal strength, a printed circuit television H-pad product was introduced. Individual units could provide 10–40 dB attenuation in a PEC configuration. Expanded coverage to the switch lines and ceramics were also included in this catalog. It stated, "CRL has been producing fine ceramics since 1928." This was clearly a reference to the first fixed resistor products introduced at that time.[120]

By April 28, 1953, Centralab boasted seven production plants in the United States and Canada. The most notable products in general catalog No. 28 were the expanded line of "Convenience Kits." These featured a group of most often used parts, be it resistance controls, capacitors, or switches. Packaging consisted of plastic divider boxes for small quantities or metal cabinets for larger assortments. An example of the model BA cabinet kit is shown in Fig. 47. It consisted of 22 Blue Shaft controls having C2 audio tapers of either 0.5 or 1 MΩ resistance. Separately, the model BB kit contained a series of controls ranging from 1,000 Ω to 5 MΩ, primarily in C1 linear tapers, plus on/off switches. Another television product, the PCH-4 TV attenuator, made its first appearance. It offered signal attenuations of 10–40 dB in 10 dB increments by incorporating the four individual

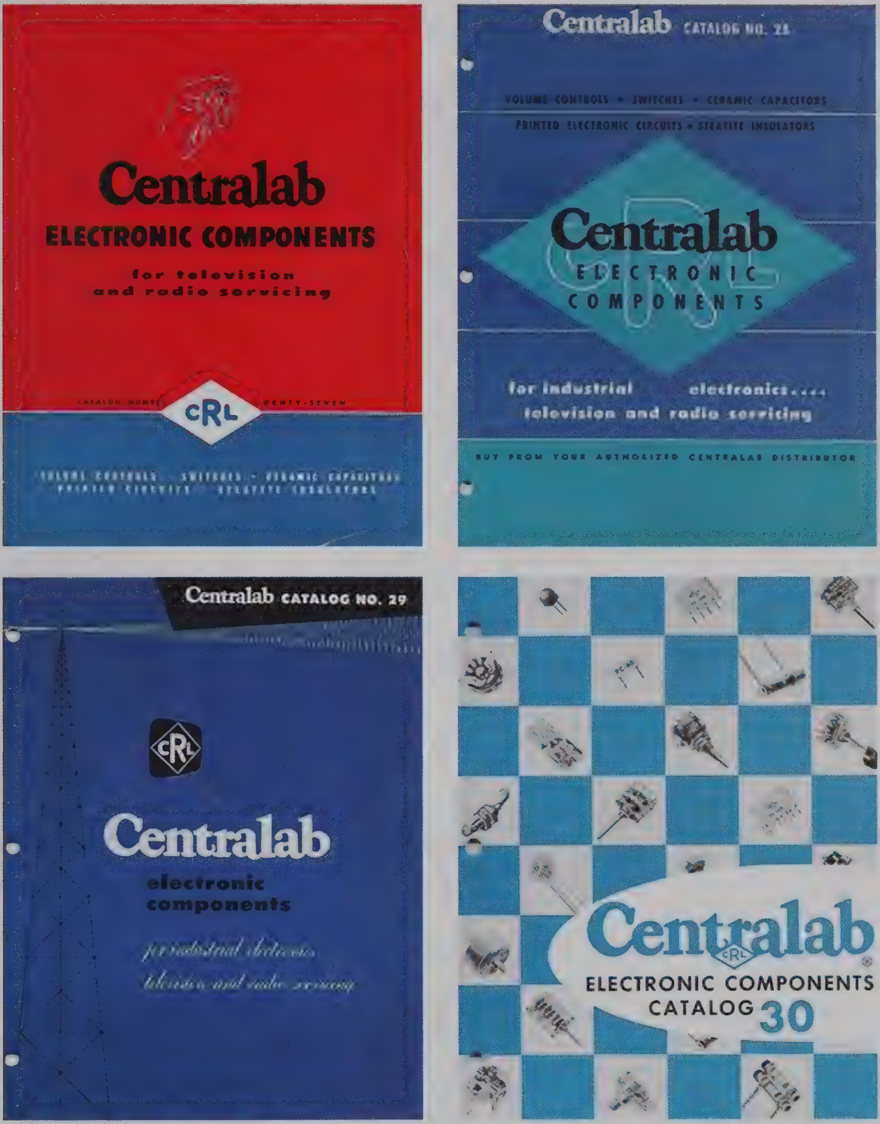

Centralab
ELECTRONIC COMPONENTS
for television and radio servicing
CATALOG NUMBER TWENTY-SEVEN
CRL
VOLUME CONTROLS · SWITCHES · CERAMIC CAPACITORS
PRINTED CIRCUITS · STEATITE INSULATORS
Centralab CATALOG NO. 28
VOLUME CONTROLS · SWITCHES · CERAMIC CAPACITORS
PRINTED ELECTRONIC CIRCUITS · STEATITE INSULATORS
Centralab
ELECTRONIC COMPONENTS
for industrial electronics....
television and radio servicing
BUY FROM YOUR AUTHORIZED CENTRALAB DISTRIBUTOR
Centralab CATALOG NO. 29
CRL
Centralab
electronic components
for industrial electronics
television and radio servicing
Centralab
CRL
ELECTRONIC COMPONENTS
CATALOG 30

Fig. 45. *Centralab* general catalogs, No. 27–30, ca. 1951–1957. (Author)

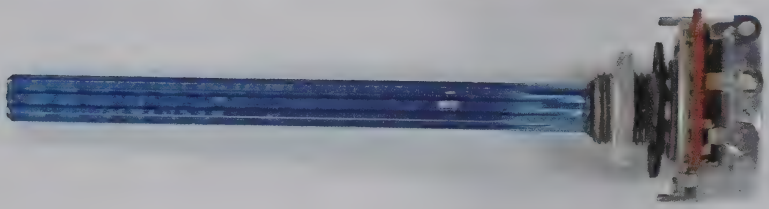


Fig. 46. Centralab Blue Shaft volume control. (Author)

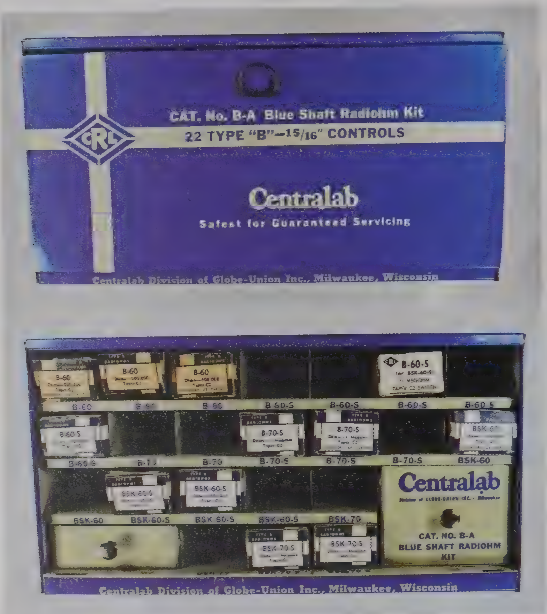

CAT. No. B-A Blue Shaft Radiohm Kit
22 TYPE "B"—15/16" CONTROLS
Centralab
Safest for Guaranteed Servicing
Centralab Division of Globe-Union Inc., Milwaukee, Wisconsin
Centralab
CAT. NO. B-A
BLUE SHAFT RADIOHM KIT

Fig. 47. Blue Shaft B-A replacement kit, ca. 1952. (Author)

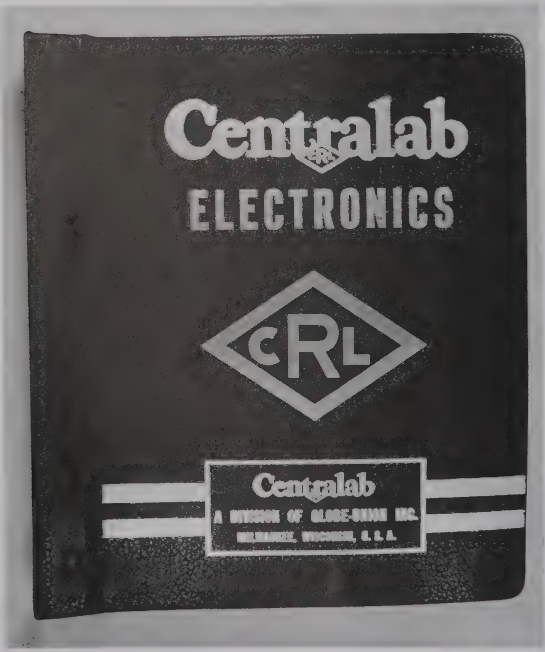


Fig. 48. Centralab *Salesman's Binder*, ca. 1954. (Author)

H-pad circuits with a Centralab selector switch in a single package for service use or permanent installation. An expanded listing of 11 PEC functional classes was provided.[121]

One of the best product reference sources of the period is the salesman's or distributor's binder (Fig. 48). At a size of 10¼" × 12" × 2" thick, this was a compendium of the Centralab product lines. This binder appeared through the 1950s with some variation in contents, consistent with the particular year it was assembled and perhaps the needs of the targeted customers. During the 1952–1954 period, this compendium consisted of eight major product sections: General Catalog, Ceramics, Tubular Capacitors, Special Capacitors, Trimmers, Controls, Switches, and PEC. In this example, general catalog No. 29 was included with Industrial Discount Lists dated January 1, 1953, and October 1954, which were not catalog-specific. The Ceramics section introduced the Centralab standard and custom fabrication capabilities and products for ceramic components. The *Engineered Ceramics Bulletin* (Form 42-221, 1955) provides an excellent explanation of the types of ceramics available, their processing, and process photos. Pricing for JAN ceramic standoffs and feedthroughs, are provided in forms 42-181R1 (12-1954) and 42-214 (4-1954), tubular capacitors, shown in Fig. 49, continued to offer the zero- and negative-coefficient products originally introduced prior to WWII. The Special Capacitors section proved to be a catch-all for many variations of ceramic capacitors that were the fruits of Centralab's wartime development of ceramics expertise. Included are the ubiquitous bypass and coupling disc capacitors (470 pF–0.02 µF @ 500 VDC); cylindrical precision RF (5–1000 pF @ 500 VDC), television high voltage (500 pF @ 10–30 kV), and transmitting capacitors (25–500 pF @ 7.5–20 kV), as well as various bushing, feedthrough, and stand-off capacitors. The Trimmers section included six different designs and specifications including dual and tandem devices. A scene of trimmer production is illustrated in Fig. 50. The Controls section consisted of a copy of *Volume Control Guide* No. 14. The Switches section offered a series of bulletins and *Engineering Preview Bulletins* for both ceramic and Bakelite switch designs. Fig. 51 shows assembly of switches. The last section, PEC, contained *PEC Guide* No. 3, a series of specialized bulletins, and a reprint of *Printed Circuit Components* by W. W. Hensler that discussed Centralab PEC construction, types, and applications. The article originally appeared in the *Howard W. Sams PF Index and Technical Digest* No. 35, Nov.–Dec. 1952.

By 1955, general catalog No. 29 made its appearance. A unique feature of this

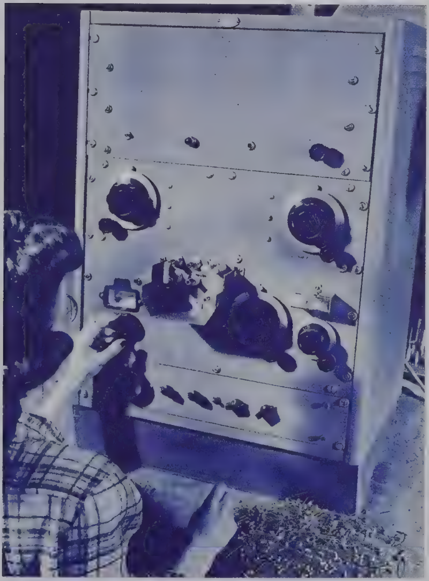


Fig. 49. Tubular capacitor testing. (Centralab *Salesman's Binder*, ca. 1954)

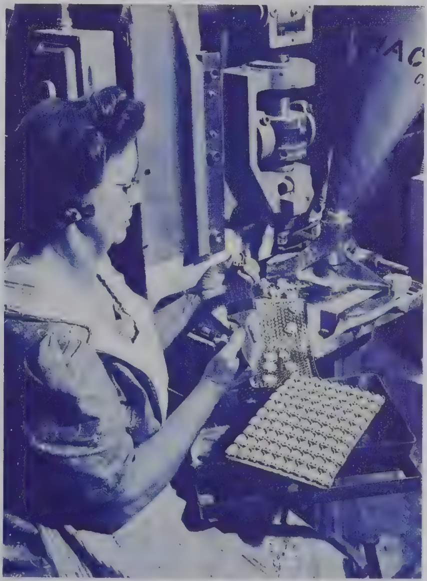


Fig. 50. Trimmer assembly operation. (Centralab *Salesman's Binder*, ca. 1954)

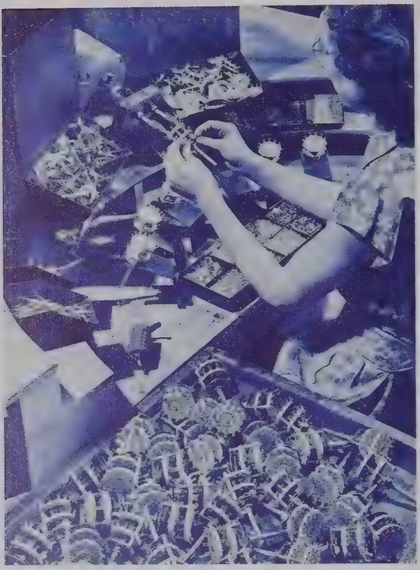


Fig. 51. Switch assembly operation. (Centralab *Salesman's Binder*, ca. 1954)

edition included pricing for a variety of products. A new dual concentric control line was introduced, Fastatch. Fig. 52 is an illustration of the assembly system that consisted of snap-together two variable resistors on concentric shafts and an optional on/off switch. This system was designed to provide convenient assembly of dual controls and adaptive shafts for the service tech. This product line would see many years of life. This catalog also expanded the AMPEC line to include the AMPEC 3 in either zero bias output or grid bias configurations. A redesigned PCH-4 Television Attenuator Switch was expanded to provide attenuations of 0–40 dB, as in previous models, plus an additional setting for 60 dB attenuation. This unit listed for $7.50 at the time. During this period, the *Pocket Edition Control Guide* (for televisions) was published quarterly to keep pace with the rapid growth of television sets. The 3¾ × 8½ format publication was available for a nominal charge.[122]

Many of the previous products continued to be offered in general catalog No. 30, ca. 1957, with some expansions. More notable was the discontinuation of the Blue Shaft line and the disappearance of engineered ceramics. Noteworthy new products included an extensive expansion of low-voltage disk capacitors for the growing field of transistor applications. Working voltages included 30, 75, 150, and 250 VDC. The Fastatch line was expanded to include a kit cabinet of the most popular parts. A typical FR-22A Fastatch kit cabinet, Fig. 53, contained 11 front and 11 rear units having several resistance tapers. Front units ranged from 1,000 ohms to 2 megohms, while rear units ranged from 50,000 ohms to 1 megohm. Additional parts included on/off switches and shaft bushings. A natural extension combining Centralab's semiconductor and PEC amplifier products was the release of the TA-6 and TA-7 single-transistor subminiature audio amplifiers. For more demanding applications, the four-transistor model TA-11 was also available. To address the sound quality of current radio and other audio applications, the Compentrol, which featured a variable resistor having either a PEC-60 or PEC-61 circuit attached, was introduced.[123] The PEC circuits consisted of a resistor-capacitor combination to enhance bass response. To promote this new application, a cardboard countertop display was offered. It featured a lighted display of half or the

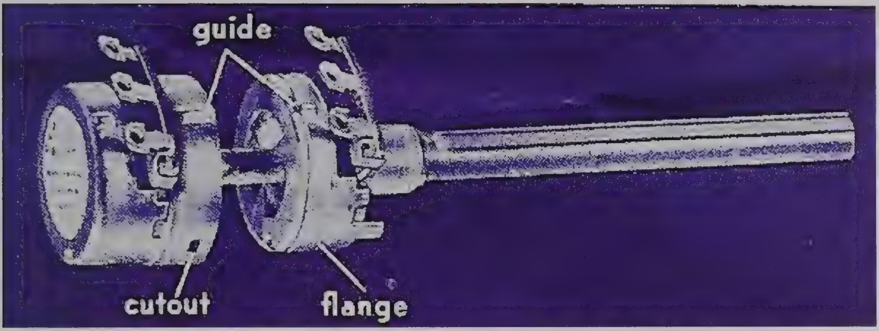


Fig. 52. Fastatch control illustration. (Centralab *Instruction Form* 42-217R, 6-56)

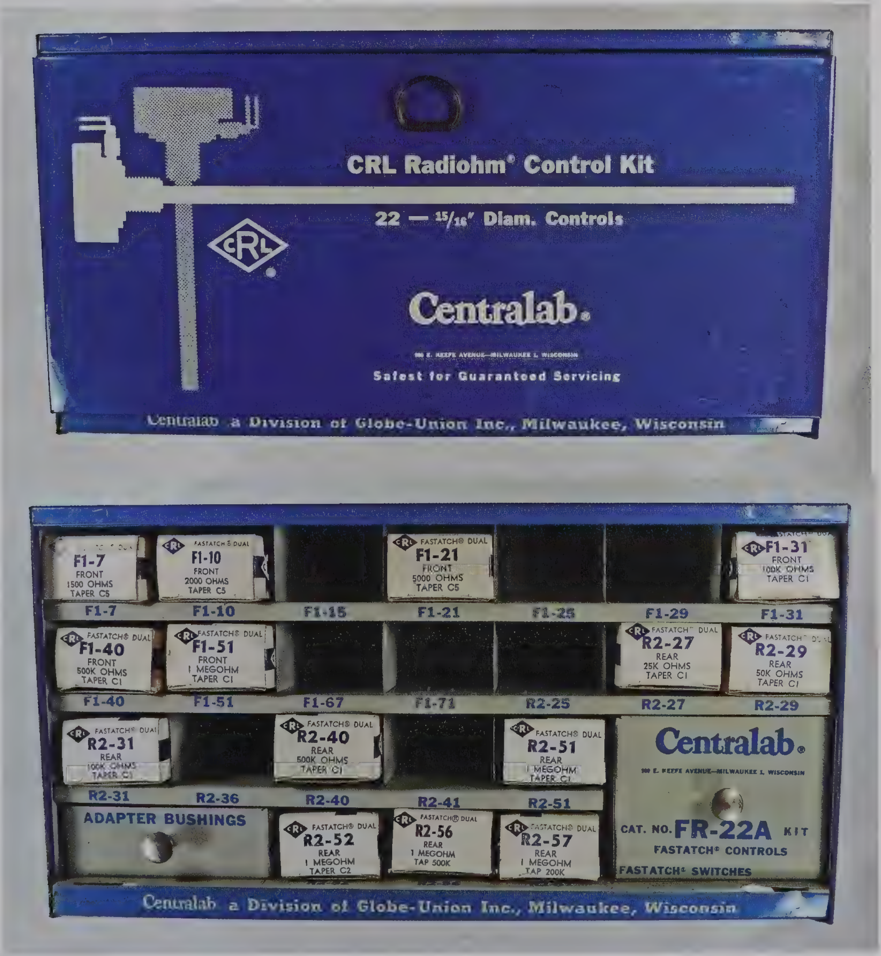


Fig. 53. Fastatch service kit and contents. (Author)

whole of an orchestra image, with the implication that you would only hear half of the program without Centralab components. Fig. 54 illustrates the unlit and fully lit display.

The final general catalog of the decade, No. 31, appeared ca. 1959–1960. It is unusual in its significantly reduced size, twenty 8½ × 5½ pages. This was likely a cost-saving measure, given the difficult business climate that started in 1957. Product offerings appeared to be extensions of earlier catalog items. Capacitors, controls, PEC, and switches are listed, along with some pricing information. Several kits for controls, switches, and PEC were offered at prices ranging from about $45 to over $250. Five domestic plants and one in Canada were listed. Operations at the Denville, NJ, plant had been discontinued and consolidated at other locations.[124]

From the late 1940s through the 1950s product packaging and promotions

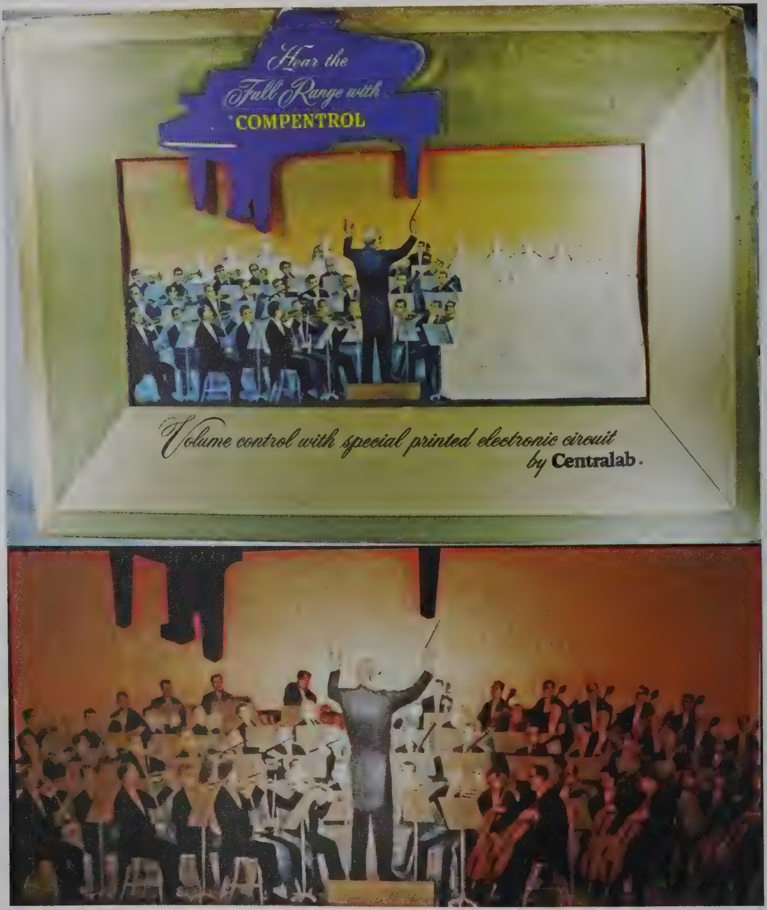


Fig. 54. Compentrol countertop advertising display. Top unlit, bottom lit. (Author)

evolved. The general evolution of the box design is illustrated in Fig. 55. The variable resistors initially used a blue and white box introduced around 1942. By the early 1950s, a significantly different design was introduced, presumably to coincide with the introduction of the Blue Shaft variable resistor line. The design featured a blue background and two long shaft controls at right angles with the CRL diamond trademark at their intersection. In addition to single-part sales, bulk packs of five replicate parts were available. As the product line evolved, a revised version of the individual packaging as well as the convenience kit cabinet appeared. While similar to the previous designs, the CRL diamond had disappeared and the overall design was simplified. The packaging evolved to a white background with blue highlighting. This design would continue into the late 1950s. Around 1959, a new design incorporating a symbolic atom figure appeared. Similar packaging styles were used for switches throughout the years. With the introduction of high-fidelity audio, an additional piece of packaging appeared, emphasizing the hi-fi application (Fig. 56). By the end of the decade, bubble packaging featuring a replaceable cardboard back was offered for small quantities of capacitors, ranging from one to five units per pack. Packaging came in two sizes to conveniently fit a 6" × 4" × 11" steel single-drawer box, 2¼" × 3⅛" for smaller or single parts, and 4⅝" × 3⅛" for larger capacitors. A close examination of the packaging shown in Fig. 57 reveals that the parts are rated in both working volts (WVDC) and tested volts (TVDC). Typically Centralab tested capacitors at twice their working voltage and showed both values on the package.

By the close of the 1950s, the Centralab Division with six manufacturing

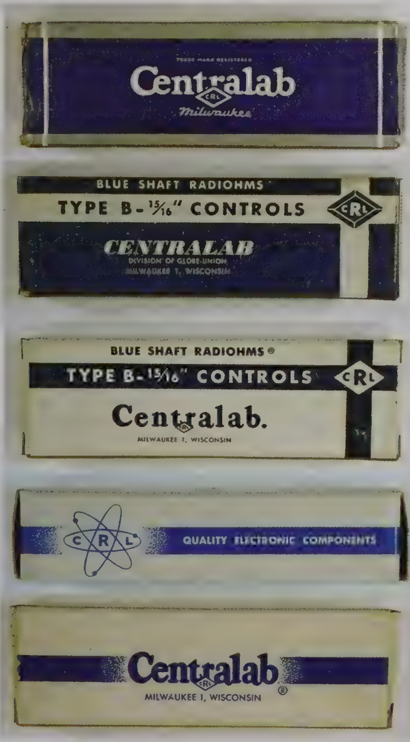


Fig. 55. Centralab volume control boxes, ca. 1942–1959. (Author)

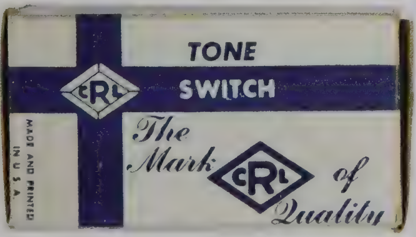


Fig. 56. Centralab hi-fi tone switch control box, mid-1950s. (Author)

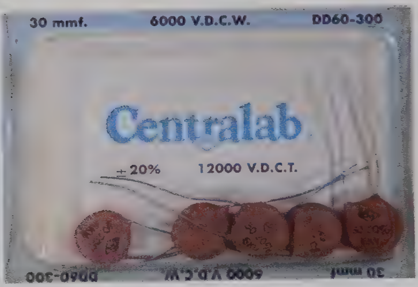


Fig. 57. Centralab plastic bubble pack for small parts and quantities, late 1950s. (Author)

sites was faced with a declining market, although its parent, Globe-Union, while challenged by the general recession of 1957–8, appeared to be in a secure position. Challenges to Centralab's business included the rapid expansion of transistor technology and, perhaps less apparent at the time, the penetration of Japanese electronics into the western markets. By 1958, the Globe-Union board elected C. O. Wanvig, Jr., as President. C. O. Wanvig, Sr., at age 68, retained his position as Chairman of the Board. Unfortunately, the decade would see the unexpected and tragic death of C. O. Wanvig, Sr., on March 18, 1959, closing another era of the Centralab story.[125] What would the future hold under the leadership of his son and successor, C. O. (Chet) Wanvig, Jr., in the face of a changing world of electronics and global competition? Only time would tell.

APPENDIX

Selected U.S. patents by Jack Kilby et al. See Fig. A1, Fig. A2, Fig. A3, and Fig. A4 for selected pages of these patents. The complete patent descriptions can be found in the U.S. Patent Office.

Endnotes

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2. *Volume Control Guide*, Centralab Form 1120, May 1940.
3. *Volume Control Guide*, Canadian edition, 1941.
4. *Centralab* catalog No. 23, Centralab Form 1001C, May 1941.
5. *Product and Facility Development History*, Anonymous, Globe-Union internal document, ca. 1963.
6. *Volume Control Guide*, 10th edition, Centralab Form 1121, Jan. 1942.
7. W. S. Parsons, *General Historical Pre-War*, Centralab Division of Globe-Union, Inc., Jan. 14, 1946.
8. *Radio Retailing Today*, Oct. 1942, Vol. 27, No. 10, p. 25.
9. W. S. Parsons, *General Historical Pre-War*. Steatite is a form of magnesium silicate known for its high dielectric strength, low dielectric constant, and low moisture absorption which makes it suitable for high frequency insulating applications including RF switches, tube sockets, standoffs, and electronic substrates.
10. W. S. Parsons, *General Historical Pre-War*.
11. *Centralab* catalog No. 24, Centralab Form 1001D, July 1943.
12. *Winning Power*, Vol. 1, No. 9, Globe-Union, Inc., July 1943.
13. *Winning Power*, Vol. 1, No. 4, Globe-Union, Inc., Feb. 1943.
14. *Winning Power*, Vol. 1, No. 5, Globe-Union, Inc., Mar. 1943.
15. *Winning Power*, Vol. 1, No. 6, Globe-Union, Inc., Apr. 1943.
16. *Winning Power*, Vol. 1, No. 9, Globe-Union, Inc., July 1943.
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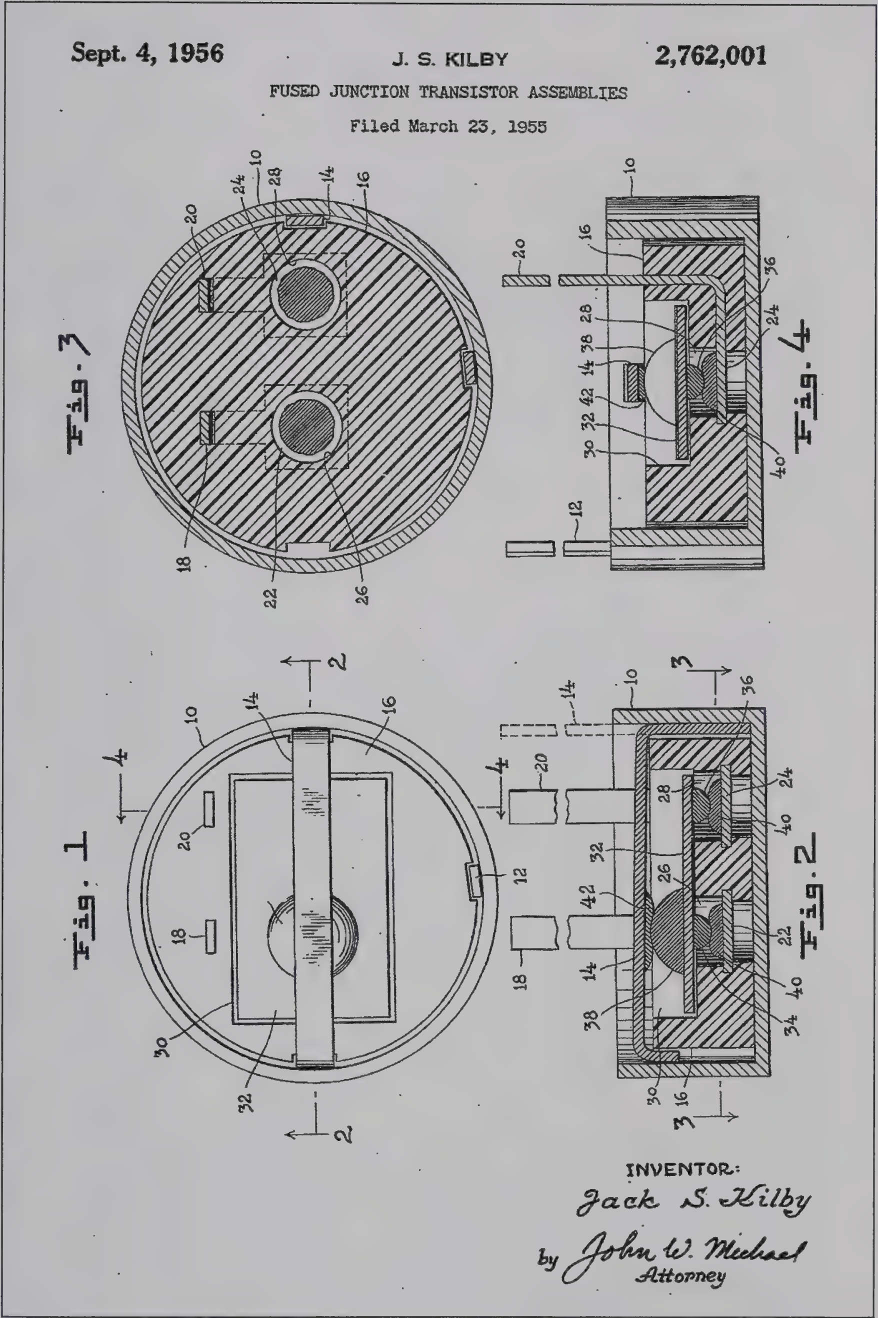


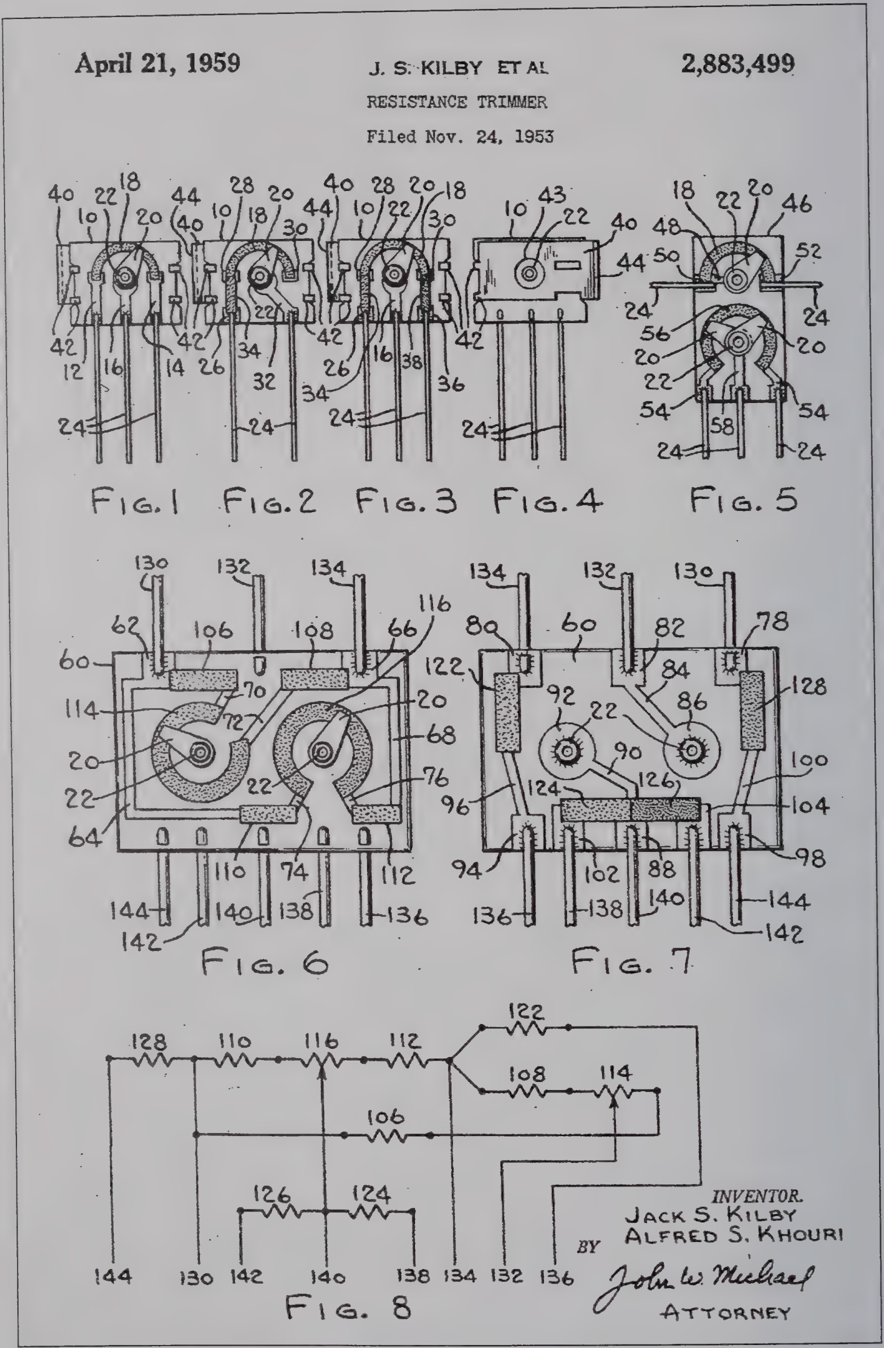
Sept. 4, 1956 J. S. KILBY **2,762,001**

FUSED JUNCTION TRANSISTOR ASSEMBLIES

Filed March 23, 1955

INVENTOR:
Jack S. Kilby
by John W. Michael
Attorney

Fig. A1. “Fused Junction Transistor Assemblies,” U.S. Patent 2,762,001, filed Mar. 23, 1955, issued Sept. 4, 1956.



April 21, 1959 J. S. KILBY ET AL 2,883,499

RESISTANCE TRIMMER

Filed Nov. 24, 1953

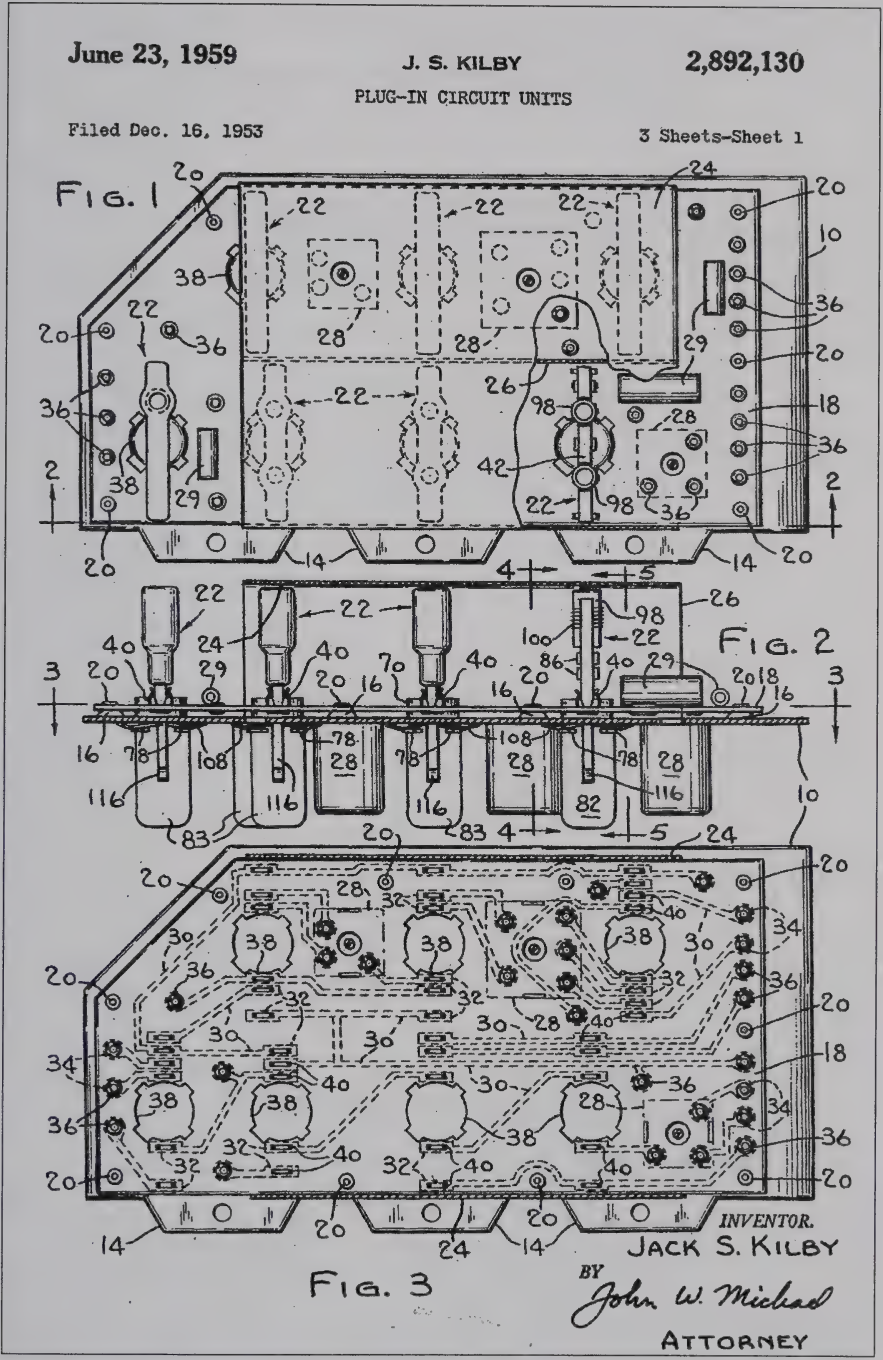
FIG. 1 FIG. 2 FIG. 3 FIG. 4 FIG. 5

FIG. 6 FIG. 7

FIG. 8

INVENTOR.
JACK S. KILBY
ALFRED S. KHOURI
BY
John W. Michael
ATTORNEY

Fig. A2. “Resistance Trimmer,” U.S. Patent 2,883,499, filed Nov. 24, 1953, issued Apr. 21, 1959.



June 23, 1959 J. S. KILBY **2,892,130**

PLUG-IN CIRCUIT UNITS

Filed Dec. 16, 1953

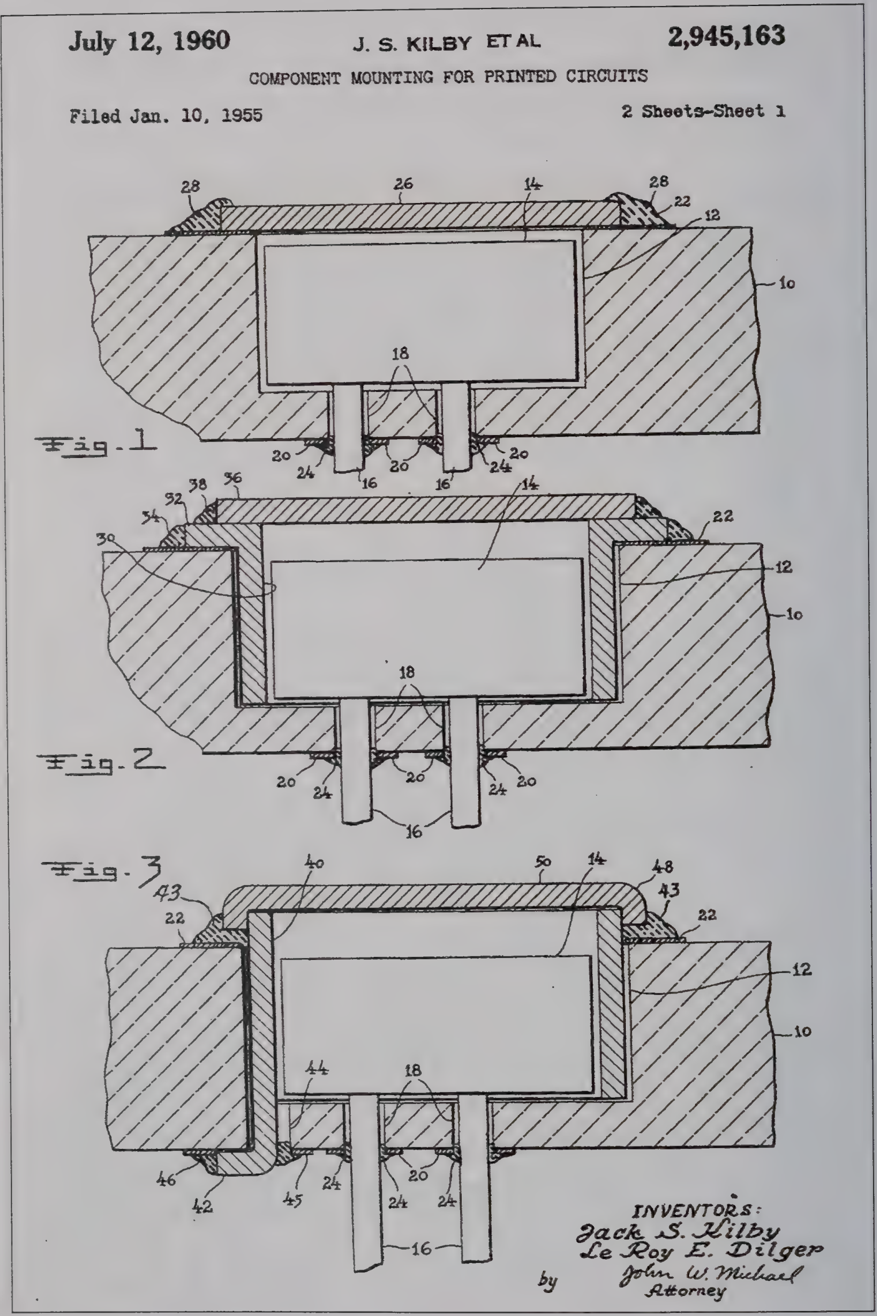
3 Sheets-Sheet 1

INVENTOR.
JACK S. KILBY

BY John W. Michael

ATTORNEY

Fig. A3. “Plug-In Circuit Units,” U.S. Patent 2,892,130, filed Dec. 16, 1953, issued June 23, 1959.



July 12, 1960 J. S. KILBY ET AL **2,945,163**

COMPONENT MOUNTING FOR PRINTED CIRCUITS

Filed Jan. 10, 1955 2 Sheets-Sheet 1

INVENTORS:
Jack S. Kilby
Le Roy E. Dilger
by John W. Michael
Attorney

Fig. A4. "Component Mounting For Printed Circuits," U.S. Patent 2,945,163, filed Jan. 10, 1955, issued July 12, 1960.

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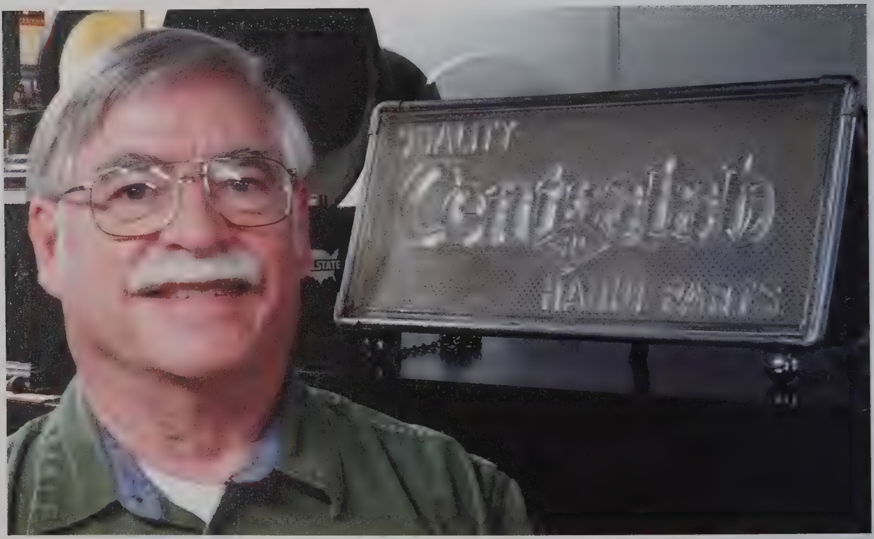
About the Author

Following completion of his post-graduate education and work as an environmental analytical chemist, **Glenn Trischan** chose to return to the Milwaukee area when offered a job in the Corporate Applied Research Group of Globe-Union. Although the Centralab Division was sold within the year following the acquisition of Globe-Union by Johnson Controls, Inc., Glenn directed materials projects cutting across the Johnson Controls product lines, including building controls, laboratory design and construction, advanced and automotive batteries, and automotive components. After over 30 years of service, Glenn retired as Manager of the Lithium-Ion Cell Development Laboratory at Johnson Controls.

Glenn's interest in radio, television, and electronics in general dates back to grade school, when the family's idled prewar Zenith model Kenwood was rejuvenated and started receiving shortwave broadcasts. He is a native of the Milwaukee area with interests in both local history and radio collecting. Early during his employment, he learned of the Globe radio products. Quite casually he and his very patient wife, Edna, began to search antique stores and local flea markets in search of elusive examples. It was at one such flea market that a chance encounter with Bob Paquette opened the door to the world of radio clubs and radio swap meets. In radio collecting, one thing always leads to another, and soon there was an unexpected proliferation of Globe radios and artifacts along with other interesting radios and paraphernalia, which provide the basis for his works. His interest in further documenting the Globe and Central Radio Laboratories lines continues. He also collects wireless and battery-operated apparatus built in Wisconsin and Iowa.

Glenn is a founding member of the Wisconsin Antique Radio Club. In addition to AWA, he holds memberships in a variety of radio clubs around the country. He has previously authored an article on Lee De Forest and the American Wireless Telegraph Company, published in Volume 14 of the *AWA Review*, and also "The Radio Products of the Globe Electric Company," published in Volume 24. The first part of this story, "The Early History and Products of Centralab Through the 1930s," was published in Volume 35 of the *AWA Review*.



Glenn Trischan

Allied Analysis of Electronic Transmissions in WWII

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During WWII, the most common method of locating enemy radio transmissions was through the use of radio direction finding, whereby two or more monitoring stations would obtain bearings on enemy transmitters and then triangulate the results to obtain a fix. There were at least two other techniques that could provide data or intelligence about the characteristics of the transmitter making the transmission and the Morse code sending-style of the operator. These techniques were known as Radio Fingerprinting (RFP) and a code-named process called TINA, which were used by the Allies. When used jointly, TINA and RFP were known as "Z" intelligence or "Z" service in the Commonwealth countries. TINA was derived from the last four letters of the word "Serpentina," a name used for the method of recording hand-sent Morse transmissions on paper tape for later analysis. As with many other WWII activities, RFP and TINA were shrouded in a cloak of secrecy. Finally, the methods and results of noise investigation are described.

Radio Fingerprinting

Radio Fingerprinting was the process used to catalog a specific transmitter through its distinct characteristics with the aim of locating it at a future date. The idea was to identify individual transmitters by their emitted waveform. The rectified signals were applied to a cathode ray tube and photographed onto moving film.

The German naval transmitters were remarkably uniform and showed little more than an initial damped oscillation produced, perhaps, by a carbon pile voltage regulator. The Italian naval transmitters were erratic and never looked the same twice in a row while their shore stations could often be identified by the ripple frequency of anything but 50 Hz (Fig. 1).

RFP was a very useful technique in certifying Allied transmitters when they were used for deception purposes. Here is just one example extracted from the book *Secret Warfare*:[1]

> "Portable transmitters were meant to emit maximum power with minimum

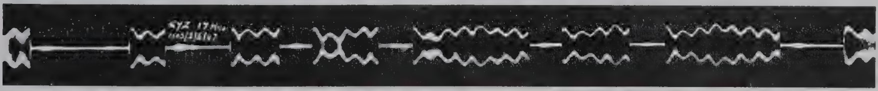

Fig. 1. This is an example of a radioteletype signal whose transmitter is slightly faulty. The keying envelope is perfectly formed except for the 100 Hz ripple riding on the signal. (Collingwood Heritage collection)

> size and more often than not, they were not provided with the necessary number of circuits for obtaining a perfect tone quality. Specifically, the British B2 and BP3 sets were stabilized with quartz crystals, but their characteristic tones could not fool the Germans about their identities. A number of these were set up on British soil and operated as phantom networks. The German interception services located this phantom network and localized it. Once they realized that the transmissions were coming from Britain, they abandoned their scrutiny of this network. At this point, Special Operations Executive (SOE) took the radios out of this phantom network as needed and dropped them by parachute into occupied territory. These sets were then added to the real clandestine network. By doing this, the German radio location services were slowly but surely led into saturation and chaos."

Note that radio fingerprinting was never meant to be used by itself. It was to be used in conjunction with other identification tools such as TINA.

TINA in the UK

TINA was the method used to recognize specific radio operators by their Morse code "fist" and habits.[2] TINA was the process that involved studying the distinctive characteristics of particular Morse code operators to identify and trace the locations of those operators, which might reveal that a particular operator has changed ships. A change in ships may indicate damage or destruction to the previous ship or even a reassignment. Each operator had a distinctive touch, or "fist." Some were slower while others were jerky. Still others held down the key or paused between dots and dashes for different lengths of time and so on.

Extracts from a TINA article written by John Roscoe, G4QK, provide a more detailed picture of TINA.[3]

> "The early TINA recordings of Morse were made with a siphon-pen recording on paper tape using a device known as an undulator [Fig. 2]. At a later date, Morse transmissions were recorded on 35 mm film with a slow-running RFP machine. This allowed measurements to be made through noisy conditions."

A bridge unit (Fig. 3) connected the receiver audio output to the input of the undulator.

In the UK, two women from the Women's Royal Navy Service (WRENS) would be assigned to analyze intercepted Morse Code signals. The women in this service were populary known as WRENS. Two WRENS at a time would start the process. One would read off the measurements from the film using an enlarger and the other transferred them to graph paper. The dashes and dots were then marked with red and blue circles. Attempts at identification with previously captured records were made by direct comparison. This procedure inevitably relied on the perception and memory of the operator on duty. This was not a fast method so two processes were used to help automate the process:

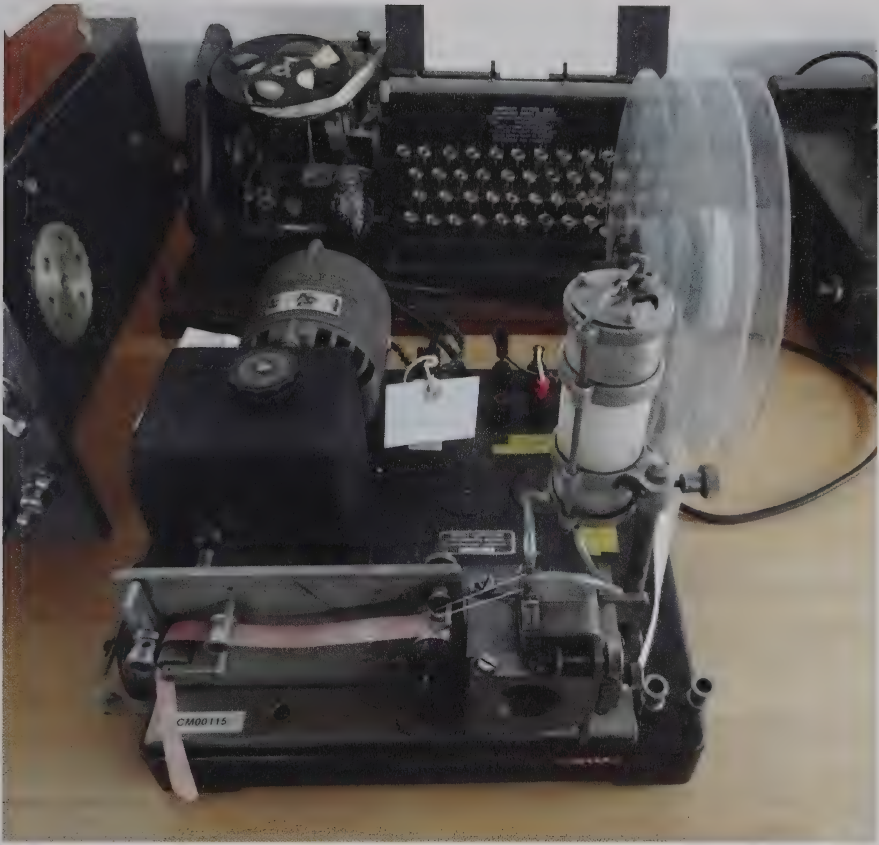

Fig. 2. UG-6 undulator. A pen records the Morse on paper tape which is then inspected for an operator's fist characteristics. (Collingwood Heritage Collection)

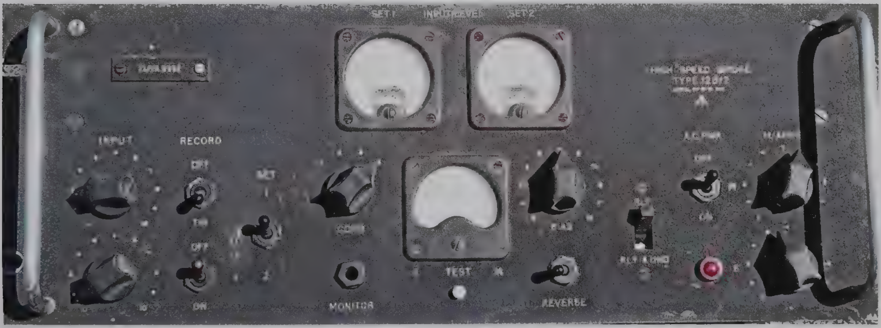

Fig. 3. Bridge unit. By arranging one or more tubes to alter the balance of a resistance bridge network across which is connected to the recorder, equal mark and space currents can be passed in opposite directions through a single coil. The device, in all of its variants, became known as a "bridge." (Photo by Clive Kidd)

(1) A method of recording that would permit simple and more rapid measurement.
(2) A machine-compatible system for classifying the records.

To summarize: On the issue of measurement, the TINA device would make a vertical deflection on the 35 mm film instead of a horizontal one. The vertical deflection would correspond to each dot or dash in the Morse character.[4]

The idea behind the mechanical classification scheme was to extract parameters from the Morse code that could be coded numerically and searched mechanically. In those pre-computer days, the best machine that was available was the Hollerith 80-column punched card sorter with a built-in 8-column group selector which worked at the astonishing rate of 400 cards per minute!

In the WWII era, Morse was sent mostly by straight key. Automatic and semi-automatic (Vibroplex-style) keys did exist in 1942, but they sent relatively clean code so it would be challenging to make an identification to a specific operator using TINA. So TINA was limited to the analysis of code generated by straight keys. In addition, sidetone oscillators were uncommon, so practically all the operators would have been sending by "feel" alone. Fig. 4 shows a test message on an undulator paper tape that was used for analysis.

The most consistent characteristic in Morse code was the ratio between an adjacent dot and dash in the longer symbols. For example, the dash might be markedly longer than the following dot in D (dah dit dit), B (dah dit dit dit), and 6 (dah dit dit dit dit). This would almost certainly be matched by a similar disparity in U (dit dit dah), V (dit dit dit dah), and 4 (dit dit dit dit dah). Invariably, A (dit dah) and N (dah dit) did not fit into this pattern. The fate of the other dots, in 4 and 6 for example, was a matter of individual taste. This simplified measurements because there was no need to establish an average length for the dot. The ratio between adjacent elements could be immediately coded on a scale of 1 to 10, with adequate provision for the spread of results.

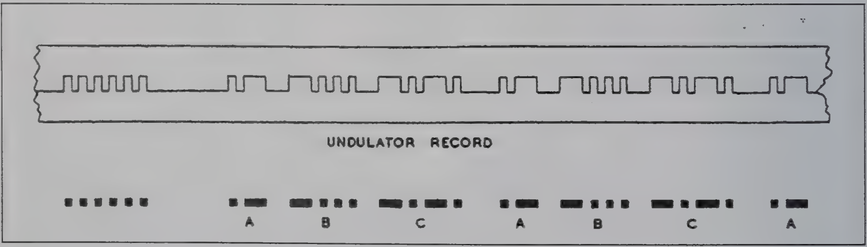

Fig. 4. Undulator paper tape record. At the top of the image is the output tape of the undulator with the corresponding Morse characters shown below. This is how TINA started, but later on, the system used photographic film. From this hard copy, the TINA operator could study the length of the dots and dashes in the character stream. (R. B. Armstrong and J. A. Smale, "High-Speed Recording of Radio-Telegraph Signals," *IET Digital Library*, Vol. 91, Issue 16, Dec. 1944)

The most interesting application of this technique was the application to U-boats in the North Atlantic. Although they carried more than one radio operator, only one appeared to do the transmitting, thus reducing the number of records that had to be maintained by TINA personnel. Mass training for the German U-boat radio operators was so standardized that their style of sending made TINA analysis difficult or impractical.

The U-boats were at sea generally for a maximum of six weeks, so a preliminary scrutiny had to be made quickly and early within this period. Of course, this was only part of the picture, as direction-finding, RFP, decryption, etc., would also have contributed their intelligence to the records database. Of course, the "victims" (i.e., the Germans) were well aware that they were being monitored but since the U-boats invariably sent short messages, quite unlike the Italian submarines, they presumably felt the risk was small.

To ensure the authenticity of messages sent from behind enemy lines, each agent was subjected to a TINA analysis of his "fist" before being dispatched to the field. This consisted of sending all the letters of the alphabet and all the numbers 0 through 9. This was recorded on paper tape that moved at 16 feet per minute. At that speed, each dot was ¼ inch long on the paper tape. The irregularities of dots, dashes, and spaces characteristic of the individual's operating style could easily be compared with the paper tape record on file.

TINA and RFP in New Zealand

In the early 1940s, at least seven New Zealand signal intelligence stations were constructed and operated as part of the British-American intelligence system. Three of these stations were set up in Awarua (ZLB), Auckland (ZLF), and Waipapakauri (WPP), which became part of the U.S. Navy's Pacific-wide direction-finding (DF) net. The purpose of the net was to locate Japanese ships and other sources of enemy radio transmissions.[5]

In 1942, a new station (RNW) joined the net. RNW was the Post Office call-sign for Renwicktown, near Blenheim, NZ. In the direction-finding stations, little was told about RNW's function except that it was a naval W/T station and that all personnel were to fully cooperate with it. The new station would be staffed by the Women's Royal New Zealand Naval Service WRENS. These WRENS were all competent operators and fluent in the Japanese Katakana code. Many years after the war, it was revealed that RNW was set up as an RFP station.

The job of the New Zealand DF net was to take radio bearings on enemy signals that were radioed from the U.S. Pacific Fleet's Headquarters (NIT) in Hawaii, and later Guam. At station RNW, the identification process was started by photographing signals, which were displayed on an oscilloscope, and examining the developed print in minute detail for any peculiarities in the received waveform. These would then be compared with previously recorded photographic strips to see if any similarities would enable the identity of the station or vessel to be made.

The RNW station itself was a two-story farmhouse taken over for the duration of the war by the New Zealand Ministry of Defence. It was at the end of a long no-exit road at Rapaura, a small village on the South Island terminating on the banks of the Wairau River. The house was altered to allow an operations room downstairs, but the radio equipment and sleeping quarters for the eight WRENS who staffed the station were on the second floor. The area surrounding the house was enclosed with a six-foot-high, barbed wire fence, with a locked gate, and security was provided by a detachment from the Guards-Vital Points that camped on the site.

It was an ideal radio receiving situation, away from all interference. There was a clump of tall poplar trees close to the house and these were used to provide masts for the inconspicuous aerial, which was erected by using a bow and arrow to sling the aerial wire between the trees. The equipment was based around a special receiver incorporating an oscilloscope and movie camera, known as REB 2, which had been sent out by the British Admiralty from London. Also provided were two Collier and Beale HRO-type receivers, fitted with oscilloscopes. This equipment was installed by an ex-Post Office telegraphist who was a leading telegraphist in the RNZVR. He remained at the station to instruct the staff in the Japanese Katakana code and left when they were proficient.

The operating procedure was to tune into the frequency and identify the callsign that had been sent from Awarua on the landline. The signals were checked on the oscilloscope attached to the standard receiver for photographic suitability. If suitable, a button was pressed which brought into operation the REB 2 equipment which then started photographing the waveform on the oscilloscope.

Later, when the film was developed, the classifier person examined the films in detail looking for imperfections such as harmonics, damped waves, key-relay effects, and anything else peculiar to that transmitter. In many cases, the operator's style of sending could be recognized and this would be a further clue to the station's identity.

The photographic strip details were recorded, given a file classification, and stored for future reference. Once a file had been built up, the station could be identified by the signal it emitted and the style of sending. This meant that no matter how often the callsigns were changed—and the Japanese changed theirs daily for a while—the station or vessel could be identified irrespective of the call sign.

The operators worked during the night, 6 p.m. to 6 a.m., on four-hour watches, and the classifiers worked during the day, examining the photographic strips that had been received overnight. If there was incoming traffic of importance during the night or if it was busy, the operators would thump on the ceiling with a broom handle to wake up the sleeping classifiers to bring them down to attend to the urgent traffic and clear the filled cassettes. The results of the classifiers' analysis would be suitably coded up and telephoned to the Navy Office in Wellington over a scrambler (inverted speech) telephone.

There were other RFP stations set up by the Admiralty; the one in the UK was responsible for identifying the German pocket battleship *Bismarck* when it broke out into the North Sea and was ultimately sunk by the Royal Navy. There was another RFP station in Sri Lanka (formerly Ceylon).

The Japanese advance southwards was blocked by the Battle of the Coral Sea in May 1942, and their offensive power was effectively broken four weeks later at the Battle of Midway. Japan was on the defensive and their large, ocean-going submarines were no longer able to roam at will. A considerable number were used to resupply their isolated garrisons under Allied blockade in the Pacific.

Enemy radio activity steadily dwindled, and in May 1944 the Rapaura Naval W/T station (RNW) was closed. The staff was transferred to the New Zealand Navy Office in Wellington to work in the Intelligence and Communications sections. During its operation, the Naval W/T station Rapaura (RNW) provided valuable insight into the characteristics of enemy signals from Japanese forces that were menacing the islands of the Pacific. It is to the credit of the WRENS that this particular specialized service was performed with discipline, diligence, and in total secrecy. All the personnel involved at RNW were held under an Oath of Silence from the New Zealand Ministry of Defence until 1982.[6]

During the war in the Pacific, a Canadian military unit called the "1 Canadian Special Wireless Group" was deployed to the Pacific Theater and conducted tactical SIGINT activities against the Japanese along with the Australian military in New Guinea. It was active from 1944 to 1945.

TINA and RFP in Canada

TINA/RFP equipment was given to the Royal Canadian Navy (RCN) by the British Admiralty in December 1941, and by January 1942, operations on an experimental basis had begun at a Department of Transport station near Ottawa. By May 1943, "Z" operations moved to the RCN station at Gloucester, Ontario, but due to the drop in U-boat W/T traffic, the RCN chose to move RFP/TINA operations to Harbour Grace, Newfoundland.

During a visit to England by Lt. Low (Royal Canadian Navy, RCN), he observed that all "Z" operations and classification work was performed by British WRENS, who were most capable for this job. The RCN based their decision on this observation and decided that Canadian "Z" operations should be operated by the Women's Royal Canadian Naval Service (WRCNS) personnel, wherever this could be done, considering the locations and amenities of the isolated Canadian stations. Two Royal Navy WRENS were requested and ultimately sent to Canada to train Canadian WREN personnel for these duties. They arrived in November 1943 and spent three months between Gloucester and the Harbour Grace stations. By 1943, using TINA, RFP, HFDF, and "Y" intercepts, the Allies, with a network of 40 stations all over the world, were able to track enemy units at sea.

TINA and RFP Operations in the United States

United States Navy work on Japanese and German fingerprinting was carried out by the USN group OP-20-G. The acronym OP-20-G stands for "Office of Chief Of Naval Operations (OPNAV), 20th Division of the Office of Naval Communications, G Section / Communications Security." It was the U.S. Navy's signals intelligence and crypto analysis group during WWII. Its mission was to intercept, decrypt, and analyze naval communications from the Japanese, German, and Italian navies. OP-20-G was responsible for TINA and RFP operations in both theaters of war. In addition, this group also copied the diplomatic messages of many foreign governments. The majority of the section's effort was directed towards Japan and included breaking the early Japanese "Blue" book fleet code. This was made possible by intercept and High-Frequency Direction Finder (HFDF) sites in the Pacific, Atlantic, and continental United States, as well as a Japanese telegraphic code school for radio operators in Washington, DC. The equipment that was used is shown in Fig. 5.[7]

Although the British RFP could distinguish between U-boat and surface vessel transmissions, the British and American RFP gave disappointing results when TINA analysis was performed. The likely cause of this was the consistency in transmitter hardware (i.e., emission quality) and good Morse operator training.

The U.S. Army Signal Intelligence Service (SIS) was another source of radio intelligence, but their group and OP-20-G were badly hobbled by bureaucracy. The groups had become rivals, competing with each other to provide their intelligence data, code-named "MAGIC," to high officials. In 1940 SIS and OP-20-G agreed to provide MAGIC on alternating days, and try to draw up guidelines for which team handled what traffic. Complicating matters was that the Coast Guard, the FBI, and even the FCC also had radio intercept operations. The result was that much of the MAGIC intelligence was unused. There was no efficient process for assessing and organizing the intelligence or getting it to the proper end

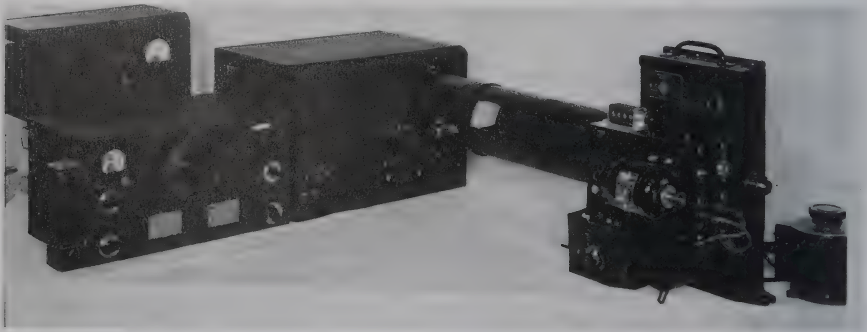

Fig. 5. Radio fingerprinting equipment used by Office of Chief of Naval Operations OP-20-G. (Extract from document *RIP480*)

users. Domestic U.S. radio intelligence was administered by the Radio Intelligence Division (RID), but their focus was to track down illegal domestic transmitters using a network of 58 monitoring stations in the continental United States.

Fleet Radio Units (FRU) were the major centers for Allied cryptological and signals intelligence during the Pacific Campaign of WWII. Initially, two FRUs were established in the Pacific, one at Pearl Harbor, Hawaii, called Station HYPO or FRUPAC (Fleet Radio Unit, Pacific), and the other, called Station CAST or Belconnen, at Cavite Naval Yard, then Corregidor, Philippines. With the fall of the Philippines to Imperial Japanese forces in April and May 1942, CAST personnel were evacuated to a newly established FRU in Melbourne, Australia, called FRUMEL (Fleet Radio Unit, Melbourne).[8]

Captain Eric Nave of the Australian Navy, commanded operators who had been monitoring Japanese preparations for war. He said that the Japanese Navy had mounted a massive deception exercise to prevent anyone from realizing that Pearl Harbor was a target. One step which undoubtedly deceived the U.S. Navy was the transfer of the wireless operators from aircraft carriers that were to take part in the Pearl Harbor attack to other ships in Japan's Inland Sea. Since the Allied intercept operators were using the fists of their Japanese counterparts to identify the various enemy radio transmissions, this move completely threw them off guard and led them to place the carrier force that was to attack Pearl Harbor in Japanese home waters.[9]

By 1958, the terms listed below were used to describe various aspects of radio intelligence. It is not evident at this time as to which other techniques were applied to the WWII era other than TINA or RFP and Noise intercept.

- Special Identification Technique (SIT) - A collective term including Morse operator analysis, radio fingerprinting, and direction finding.
- Advanced Identification Technique (AIT) - A technique of emitter identification involving analysis of unintentional variations in amplitude modulation and frequency modulation which occur in target emissions. This is the preferred term for "radio fingerprinting" or "waveform analysis."
- Emitter Location/Identification (ELI) - The process of locating or identifying an emitter through the use of one or a combination of the following techniques: direction finding, advanced identification techniques, or unintentional frequency deviation. In British usage, the preferred term is "technical aids."
- Radio Fingerprinting (RFP) - To identify and classify the unique characteristics of individual radio transmitters by the study of oscillograms of their signals. Also called transmitter identification.
- Morse Operator Analysis (MOA) - The cataloging and identification of manual Morse operators by their individual sending characteristics. Formerly referred to as TINA.
- MOrse Characteristics Analysis (MOCA) - The study and cataloging of recorded manual Morse

transmissions to identify individual Morse operators by their operator-sending characteristics.

- TINA - Former term for Morse operator analysis.
- Direction Finding (DF) - The process of determining the apparent azimuth of an emitter by the use of direction-finding equipment.
- Hull-to-Emitter Correlation (HULTEC) - The association of ELINT intercepts to a specific ship, through analysis of all available parameters of the intercept and consideration of the elapsed time and possible distance traveled by the target ship since the signal was last intercepted.
- Unintentional Frequency Deviation (UFD) - A technique of emitter identification involving analysis of unintentional phase variance of on-off keyed Morse code.

Intelligence Operations in Australia

Fleet Radio Unit, Melbourne (FRUMEL) was one of two United States-Australian-British signals intelligence units in the Pacific, the other being FRUPAC, which fed information to U.S. headquarters in Washington. Nowhere near the size of Britain's famed Bletchley Park intelligence headquarters, a few hundred people, many from the Women's Royal Australian Naval Service or female civilians, worked at Monterey, Australia.[10] America had the biggest units which received intercepts from Mornington in Victoria, Harmen in Canberra, and Townsville in Queensland. FRUMEL's biggest receiving station was Adelaide River in the Northern Territory, staffed by the U.S. Navy.

Captain Eric Nave commanded a small Royal Australian Navy cryptographic unit that worked at Victoria Barracks in Melbourne starting in 1940. Some of the WRANS at work are shown in Fig. 6.

Noise Investigation

This extract provides some details about the technique of noise investigation.

> "At the beginning of the war, intercept watch was centered entirely on radio communications, but with the advent of radar and radio navigational aids it soon became necessary to organize intercept watches for these noises in order to ascertain progress made by the enemy in using these new features of

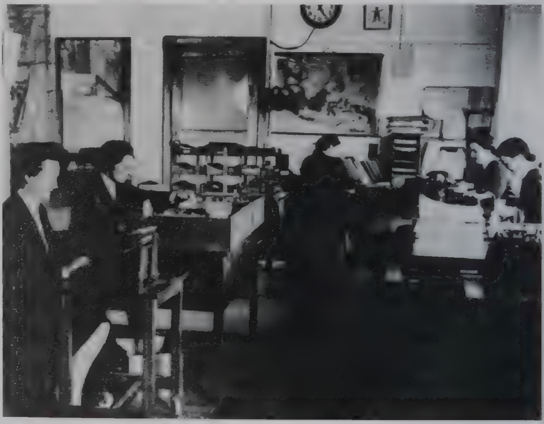

Fig. 6. Members of the Women's Royal Australian Naval Service (WRANS) working at FRUMEL on Queens Rd, Melbourne, in 1942. (Royal Australian Navy photo)

> radio and to turn such use, where practicable, to the advantage of the Allies."[11]

Noise investigation would ultimately investigate these types of emissions:

- Radar transmissions
- Navigational beacons
- High-speed communications
- Radio teleprinter links
- IFF Transmissions (Identification Friend or Foe)
- Electronic navigational aids
- Jamming transmissions
- Meteorological balloon transmissions

The first naval noise investigation was carried out towards the end of 1940 to determine the characteristics of the enemy radar in the Pas de Calais area of France so that suitable countermeasures could be initiated for the protection of Allied convoys. At much the same time, assistance was given to the RAF in explaining how to counter the radio aids used by enemy bombers over the United Kingdom. The RAF organization expanded continuously from 1940 onwards, since, once they had effectively countered the enemy aids over the UK, they were called on to assist in the Allied bomber offensive over Europe by upsetting the German radio warning and control systems there.

The naval effort, however, marked time until about 1942, as there were few important German naval noises to analyze. The commencement of large-scale amphibious operations was the next objective. It was soon clear that, if assaults were to achieve any tactical surprise and avoid crippling damage from radar-controlled coastal batteries, careful reconnaissance of enemy coastal radar and initiation of suitable countermeasures was essential. The problem became more acute as the Allies got closer to the heart of enemy resistance where the German coastal defenses became stronger.

The problem was not only one of obtaining intelligence to enable jammers to be designed, but also to provide noise investigation personnel and equipment to specific ships so that any jammers fitted could be used to the best advantage. In most amphibious operations, noise investigation equipment and personnel were always in short supply. Towards the end of the war, a measure of standardization was achieved in the equipment and personnel supplied to ships.

Meanwhile, the Americans in the Pacific had been faced with a rather different noise investigation problem. There, distances were great and besides amphibious operations, there was more chance of surface engagement and attacks by enemy naval aircraft. Information was sorely needed about enemy coastal radar, both for long-range amphibious assaults and for air strikes on shore targets—particularly to discover "blind" radar areas in which forces (both sea and air) could approach undetected. Information was also needed on the enemy ship and airborne radar so that appropriate countermeasure equipment could be supplied. Much use was made of specially fitted "Ferret" aircraft to obtain this information. As a result, noise investigation developed rapidly in the U.S. Navy. Their results were communicated freely to the Brits and steps were in hand at the end of the war to bring the British Pacific Fleet up to the same standard.

A further use of noise investigation under development at the end of the war was the tactical possibility of locating enemy radar transmissions and using this knowledge to evade or take up an advantageous position; the value of this depended on the fact that radar transmissions can be intercepted well outside radar detection range. Naval noise investigation started ashore but its future would lie mainly at sea and in the air since radar ranges are comparatively short and shore stations can only intercept them when the enemy is close at hand.

The Results of Noise Investigation

Practically all successful radar countermeasures were initially due to noise investigation. The main successes were:

- The analysis of the enemy coastal radar chain in the Straits of Dover; successful jamming of the enemy coastal radar in amphibious operations thus permitting a measure of tactical surprise and subsequent protection against coastal batteries.
- Masking of feint operations by deliberately inadequate jamming, so that the enemy should "see" something but be unable to determine details.
- The general success of the U.S. Navy in the Pacific in analyzing Japanese radar.

There are no known photographs of early REB or REC equipment; however, Clive Kidd of the Collingwood Heritage collection provided some elementary descriptions:

> "The B40 receiver (a 1950s design), also known as outfit CDW (from handbook BR222) has two sockets: SK202 and SK203. These are for REB and REC equipment. REC (SK202) is the output from the detector and is an audio output [described as DC]. It was designed to record audio to a disc, i.e., a shellac disc as per the old 78 records on a piece of kit known as REC. It could also be connected to an audio tape recorder, wire or tape. No further info was found on this equipment."

Some later REB equipment is shown in Fig. 7.

Range Estimation Equipment (REA)

Range Estimation Equipment was developed by the British during the war as an ancillary to HFDF fixing. It consisted of taking measurements of the path differences between various incoming rays appertaining to the same signal, and, by correlating these differences with current ionospheric data, estimating the distance of the transmitter.

In 1944, after a great deal of experimental work, a method of analyzing results evolved which enabled some 80 percent of experimental intercepts to be assessed for range with a 10 percent accuracy. The scheme never became a practical success as it was complicated and suffered from many difficulties.

Going Forward

Now let's fast forward to the mid-1960s. Noise investigation and RFP became a routine function of the Electronic Warfare offices in the ships of the world's

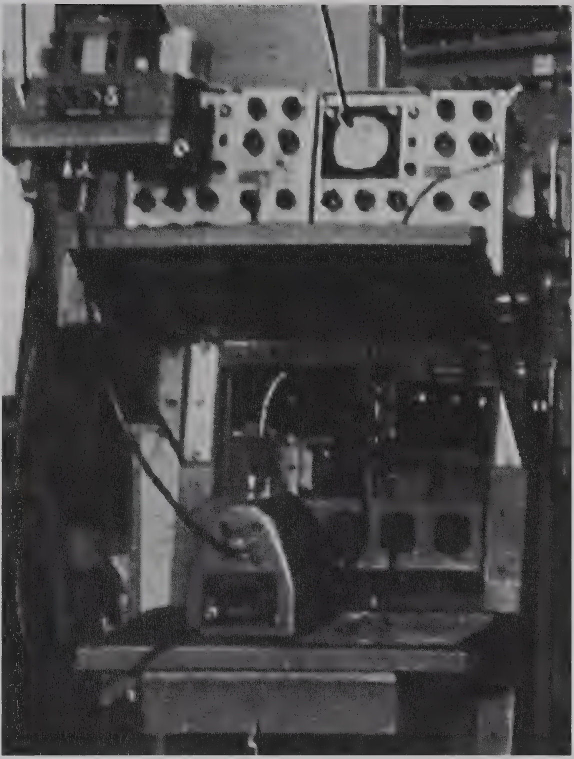

Fig. 7. (Right) This is a Royal Navy REB 6 device fitted into a 1950s-era COMAL (Communications Analysis) bay. The camera and oscilloscope are at the top left corner of the photo. (Collingwood Heritage Collection)

navies. In 1967, the Royal Canadian Navy developed an electronic "pop-up" radar emitter identification system called the Electrofile (AN/ULX-501) for the IRE and DDH 280 classes (destroyer) of ships. This was the first form of automation to speed up the process of identifying radar emitters. It moved the state of the art from operators having to look up possible emitters in a book (a slow process) to a rapid presentation of a list of possible emitters given the frequency, pulse repetition rate, and power level. This system then became the forerunner of today's CANEWS automated system. Today, electronic countermeasures are classified so any RFP operations would still be masked in secrecy.

With the navies of the world discontinuing CW communications mainly in the 1980s and 1990s, there was no further need for TINA so there is not much more that can be said about it. RFP, on the other hand, continues on in its various forms. Hopefully, this research has helped provide an overview of TINA/RFP operations. Any feedback about this article can be sent to: jerry.proc@sympatico.ca.

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About the Author

Jerry Proc, VE3FAB, a resident of Etobicoke, Ontario, has been a licensed amateur radio operator since 1964 and also holds an Advanced Amateur Radio Operator's Certificate. His interest in electronics was sparked at a very young age, and during the 1960s Jerry developed a fascination with military radio gear. In 1970, he graduated with a diploma in Electronics Engineering Technology from the Radio College of Canada. Later, he obtained an Advanced Networking Certificate through Continuing Education Studies program at Humber College, Etobicoke, Ontario. Jerry has served in both a technical and managerial capacity in the mainframe computer and data communications field since 1970 and is currently retired from Bell Canada where he was employed as a network support specialist.

Jerry Proc

The Story of How Lee De Forest Developed the Audion

Part I. The History of De Forest's Published Accounts

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Lee De Forest's many accounts of how he invented this three-electrode audion invariably began with an account of how he developed his two-electrode audion, a development that he claimed was an integral step in the development of the three-electrode audion. De Forest also claimed that he developed his two-electrode audion without any knowledge of John Ambrose Fleming's very similar oscillation valve. De Forest published two extensive but conflicting accounts about how he developed his two-electrode audion, one at a lecture to the American Institute for Electrical Engineers in October 1906, and the other at a lecture to an audience of his peers at the Franklin Institute in January 1920. The differences between these two accounts are dramatic and cast doubt on the credibility of both. It turns out that De Forest provided a third and very different account of how he developed the two-electrode audion during a lawsuit filed by American Marconi in 1914 alleging that De Forest's audions infringed Fleming's valve patent. The testimony and exhibits from the trial were documented in five volumes for the participants in the lawsuits and court records, but they were never made public. The five volumes prepared for the plaintiff's attorney became available recently, so a very different version of how De Forest developed his two-electrode audion can now be told—a story that is based to a large degree on De Forest's sworn testimony and unpublished documents that he submitted as exhibits.

Historical Perspective

The two-electrode thermionic vacuum tube was important for several reasons. It was the first thermionic vacuum tube detector to be widely used in commercial communication systems, namely in the communication systems of the British and American Marconi companies. Both the British and American Marconi Companies used two-electrode valves in the Fleming Valve Receiver beginning in 1910 and ending in early 1917 when commercial message transmissions were banned during WWI.[1] The two-electrode thermionic detector was also the forerunner of De Forest's three-electrode vacuum tube,[2] which replaced the two-electrode valve in virtually all radiotelephone and radiotelegraph systems after WWI. Consequently, whoever invented the two-electrode tube could claim credit and honors for an important seminal invention that led to a revolution in communication systems and was also used in many applications other than communication systems. It also turned out that the inventor of the two-electrode thermionic vacuum tube had a valid legal claim to royalties from revenues that accrued from the use or sale of the three-electrode tube.

Both John Ambrose Fleming and Lee De Forest laid claim to having priority in the invention of the two-electrode thermionic vacuum tube, which Fleming called a valve and De Forest called an audion. Fleming filed the first patent application for his valve in the United Kingdom on November 16, 1904, and he also filed a U.S. patent application on the same device on April 19, 1905. According to U.S. patent law, his U.S. patent was accorded the same priority date as the filing date for his UK patent, namely November 16, 1904. De Forest filed the first patent application for his audion on January 18, 1906, almost two years later. However, the United States Patent Office (USPO) at that time awarded patents to the first to invent, not the first to file a patent, so if De Forest could prove he had invented a flame detector that operated on the audion principle before Fleming filed the patent application for his valve, he could present a legal argument for being awarded precedence in the invention of the thermionic valve in any litigation over priority.

The matter of priority was settled in a lawsuit that Marconi Wireless Telegraph Company of America (a.k.a., American Marconi) filed in October 1914 against the De Forest Radio Telephone & Telegraph Company, Abraham White as its president, and Lee De Forest as an individual. The lawsuit alleged that De Forest's two- and three-electrode audions infringed the Fleming valve patent. The De Forest Company countersued by claiming that the Fleming patent was not valid because Fleming had not invented anything new; they claimed he merely used an existing device in the form of an Edison effect incandescent light bulb. The De Forest Company also asserted that the Fleming valve infringed De Forest's flame detector patent because De Forest had discovered the audion principle in the form of a flame detector using a Bunsen burner before the priority date of Fleming's valve patent. They also asserted that De Forest had perfected it soon thereafter in the form of an evacuated audion bulb detector. Before the trial began, American Marconi confessed judgment in court, admitting it had infringed the De Forest three-electrode patents by using them in its commercial stations. Consequently, that issue was not before the court in the trial that took place in September 1916.

Julius Mayer issued his opinion in September 1916 by finding that the Fleming valve patent was valid and did not infringe De Forest's two-electrode audion patents. The judge found that De Forest's two-electrode audions infringed the Fleming patent, but he stopped short of invalidating De Forest's patents. He then found that De Forest's three-electrode audion patents were valid and a valuable contribution to the technology, but he also ruled that the three-electrode audions infringed Fleming's two-electrode valve patent. Judge Mayer's opinion was published in volume 236 of

Federal Reporter.[3] De Forest appealed the judge's decision, but the appellate court agreed with Judge Mayer's ruling.

While the matter was settled from the legal point of view, De Forest never accepted Judge Mayer's decision. Furthermore, it does not necessarily follow that the party who wins a priority suit in a court of law is the actual inventor. There was one noted historian in particular who believed that De Forest may have had priority in the invention of the two-electrode audion. Hugh Aitken in his well-received 1985 book, *The Continuous Wave,* gave a very detailed and balanced treatment of the events leading to the respective discoveries of the two-electrode vacuum tubes by both Fleming and De Forest. He pointed out that while Fleming filed his patent on the thermionic valve well before De Forest filed his patent on the thermionic vacuum audion, De Forest claimed that he began his search for a more sensitive detector long before Fleming discovered the Edison effect bulb was a detector. Aitken also pointed out that De Forest claimed that his detector was different from that of Fleming. Aitken speculated that it was possible De Forest conceived of the essential elements of his two-electrode audion prior to Fleming's discovery in October 1904, a discovery that may have forestalled (anticipated) Fleming's patent, and the issue became the interpretation of the existing evidence supporting De Forest's version of events. Aitken says that a dispute over which interpretation of events was correct started almost as soon as the three-element audion was announced, and the debate has been ongoing ever since. At the time Aiken wrote his book in 1985, he concluded: "It is highly unlikely that any new evidence will be uncovered to settle this issue."[4]

Indeed, Aiken provides a very impressive list of source material, but absent from his list are transcripts of the 1916 trial testimony and the associated exhibits produced in the Marconi vs. De Forest litigation. These documents, which amount to more than a foot of shelf space, surfaced a few years ago. The five volumes prepared for L.F.H. Betts of the Sheffield and Betts law firm (see Fig. 1) were passed on to Gerald Tyne and then to Jerry Vanicek. With a few exceptions, neither the testimony nor the exhibits were disclosed by either one. This author came into possession of these five volumes and studied them for several years before preparing this manuscript. The account that will be

Fig. 1. Five unpublished volumes of sworn testimony, exhibits, and summations prepared after the 1916 trial in the lawsuit of Marconi v. De Forest present an entirely different account of how De Forest developed his audions than the ones he published during his lifetime. (Author's photograph)

presented in Part II of this article, which is based on these five volumes, is believed to be the most accurate account of how De Forest invented his two-electrode audion because it is based on the sworn testimony and exhibits of the following key witnesses: Lee De Forest; George Woodworth, De Forest's attorney; John Ambrose Fleming; Henry McCandless, president of the H. W. McCandless & Company; Jacob Grogan, the McCandless Company foreman; and Roy Weagant, chief engineer for American Marconi.

Aiken also said this about De Forest's accounts: "Lee De Forest himself provided a highly plausible and internally consistent account of how the invention was made. In fact, every time he told the story it became more 'rational,' in the sense that each step in the process of invention was presented as following reasonably and naturally from what had gone on before." It is certainly true that every time De Forest recounted the story it became more rational—not because it was rational at the outset, but because he altered his account on occasion to make it seem more rational as he retold his story time and again. The claims De Forest made for events and dates in his many accounts are sketchy, contradictory, and unsupported by any documentary evidence. De Forest did not create a single document describing how he discovered the two-electrode audion before his lecture to the AIEE on October 26, 1906, which provided the most detailed account of how it was developed. If the story seemed to flow "reasonably and naturally," it was because De Forest often skipped pertinent information, such as the dates and sequences of various events. In many of his accounts, several intervening months or years often go by from one paragraph to the next—without alerting the reader to significant gaps in the time between events.

The account of how De Forest invented his two-electrode audion based on trial testimony and exhibits is significantly different from all other accounts that De Forest published throughout his life. The differences in these accounts can be discerned and appreciated only by those who have a basic understanding of De Forest's published accounts. To that end, a rather comprehensive history of the principal accounts that De Forest published is presented in this issue of the *AWA Review* as a prelude to Part II of this paper planned for the next issue of the *AWA Review*, which will present the trial account. This review of De Forest's accounts is accompanied by a critical analysis that identifies discrepancies, misrepresentations, and deceptions in De Forest's very different published accounts. This review will also provide some technical details that are particularly important for understanding the similarities and differences between Fleming's valve and De Forest's audion.

An Inventory of De Forest's Published Accounts

De Forest published any number of accounts of how he invented his two-electrode audion detector throughout his life beginning with the first account he gave at a lecture to the American Institute of Electrical Engineers (AIEE) on

October 26, 1906. That lecture was given shortly after his first U.S. Patent 824,637 for a two-electrode audion detector was issued by the United States Patent Office (USPO) on June 26, 1906. The accounts he published can be conveniently divided into six categories:

1. Lectures to his peers that were subsequently published in science and engineering journals (*Proceedings of the AIEE,*[5] *Journal of the Franklin Institute*),[6]
2. Articles and letters to the editor published in electrical journals intended for the trade (*The Electrician* and *Electrical World*),
3. Testimony that De Forest gave in the 1916 trial, a brief synopsis of which was documented by the trial judge, Julius Mayer, in his findings published in the *Federal Reporter* in 1916,[7]
4. Articles in magazines intended for radio amateurs and electrical experimenters (e.g., *Radio News and Radio-Craft*),
5. Articles appearing in magazines intended for the layperson (e.g., *Scientific American* and *Popular Science*), and
6. De Forest's autobiography, *Father of Radio*, published in 1950.[8]

Principal Documents

The most important and detailed accounts are the four that have citations to specific references in the above list. The two lectures he gave to his peers at the AIEE in 1906 and 1920 provided the most important accounts of his two-electrode audions because they had more historical and technical information than any other of his many accounts. Also, the lecture to the AIEE in 1906 was followed by two discussion sessions that provided critical comments and observations that clarified many points De Forest raised in the lecture. While the accounts in these two lectures were significantly different, the many accounts that followed the second lecture at the Franklin Institute in 1920 did not change significantly. The account De Forest gave in his autobiography published in 1950, *Father of Radio*, was copied verbatim from paragraphs that appeared in his 1920 lecture.

De Forest never explained the many significant differences in his two lecture accounts, but it will become clear in due course that the significant differences resulted from the proceedings of the trial in 1916. A few details of the account that De Forest gave at the trial were revealed in Judge Mayer's findings published in the *Federal Reporter* in 1916. However, the transcripts, documents, and other exhibits from the trial that documented how De Forest invented his two-electrode audion were never published. The most important accounts, with references, are listed in Table 1 and Table 2. These are the accounts that are addressed in this paper.

There were two discussion sessions by attendees of the 1906 AIEE lecture that provided additional and important information. One of these sessions took place in New York immediately after the meeting on October 26, 1906, and a transcript of this discussion appeared in the October issue of the *Proceedings of the AIEE* that documented his lecture.

Table 1. The most relevant accounts of how De Forest developed his two-electrode Audion.

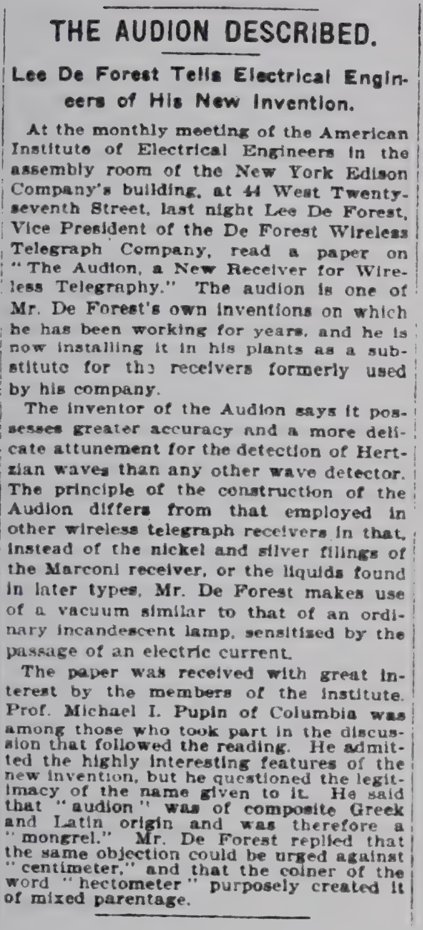
Year	Author	Venue	Audience	References
1906	De Forest	AIEE lecture	AIEE	*Proc. AIEE*, Vol. 25, p. 719
1906	De Forest	Discussion sessions (2)	AIEE	*Proc. AIEE*, Vol. 25, p. 863 *Trans. AIEE*, Vol. 25, p. 735
1906-1914	De Forest and Fleming	Letters to editors (12)	Electrical journals	See Table 2
1916	Judge Mayer	1916 Trial	Court	*Federal Reporter*, 236 F 942
1920	De Forest	Franklin Inst. lecture	AIEE	*J. Franklin Inst.*, Vol. 190, p.1

Table 2. Acrimonious letters to the editors of two journals in which Fleming and De Forest contested priority and other facts associated with the development of their respective two-electrode vacuum tubes.

Pub. Date	Author	Journal	Vol. and Page
Nov. 30, 1906	Fleming	*Electrician*	Vol. 58, p. 263
Dec. 08, 1906	Fleming	*Electrical World*	Vol. 48, p. 1117
Dec. 15, 1906	De Forest	*Electrical World*	Vol. 48, p. 1205
Dec. 28, 1906	De Forest	*Electrician*	Vol. 58, p. 425
Jan. 04, 1907	Fleming	*Electrician*	Vol. 58, p. 464
Sept. 04, 1908	De Forest	*Electrician*	Vol. 61, p. 804
Sept. 11, 1908	Fleming	*Electrician*	Vol. 61, p. 843
Oct. 09, 1908	De Forest	*Electrician*	Vol. 61, p. 1006
Nov. 21, 1913	De Forest	*Electrician*	Vol. 72, p. 285
Dec. 05, 1913	Fleming	*Electrician*	Vol. 72, p. 377
Jan. 23, 1914	De Forest	*Electrician*	Vol. 72, p. 659
Jan. 23, 1914	Fleming	*Electrician*	Vol. 72, p. 659

A second discussion session took place at the next meeting of the AIEE that took place in Philadelphia on November 12, 1906. A transcript of this discussion appeared in the *Transactions of the AIEE*, which was published in early 1907.[9]

The account De Forest gave in his 1906 AIEE lecture would not be complete without considering the numerous letters to the editors of *The Electrician* (London) and *Electrical World* (New York) that resulted from their publication of portions of De Forest's lecture. News of De Forest's AIEE lecture was published the day after the lecture in the *New York Times* on October 27, 1906, under the headline "The Audion Described" (see Fig. 2).[10] Extensive



THE AUDION DESCRIBED.

Lee De Forest Tells Electrical Engineers of His New Invention.

At the monthly meeting of the American Institute of Electrical Engineers in the assembly room of the New York Edison Company's building, at 44 West Twenty-seventh Street, last night Lee De Forest, Vice President of the De Forest Wireless Telegraph Company, read a paper on "The Audion, a New Receiver for Wireless Telegraphy." The audion is one of Mr. De Forest's own inventions on which he has been working for years, and he is now installing it in his plants as a substitute for the receivers formerly used by his company.

The inventor of the Audion says it possesses greater accuracy and a more delicate attunement for the detection of Hertzian waves than any other wave detector. The principle of the construction of the Audion differs from that employed in other wireless telegraph receivers in that, instead of the nickel and silver filings of the Marconi receiver, or the liquids found in later types, Mr. De Forest makes use of a vacuum similar to that of an ordinary incandescent lamp, sensitised by the passage of an electric current.

The paper was received with great interest by the members of the institute. Prof. Michael I. Pupin of Columbia was among those who took part in the discussion that followed the reading. He admitted the highly interesting features of the new invention, but he questioned the legitimacy of the name given to it. He said that "audion" was of composite Greek and Latin origin and was therefore a "mongrel." Mr. De Forest replied that the same objection could be urged against "centimeter," and that the coiner of the word "hectometer" purposely created it of mixed parentage.

Fig. 2. News of De Forest's AIEE lecture was published with the headline "The Audion Described" on the day after the lecture in the *New York Times* on October 27, 1906. (*New York Times*, Oct. 27, 1906, p. 9)

excerpts of this lecture were published within weeks of the lecture in prominent electrical journals in the United States and England. No sooner were the accounts of De Forest's lecture published than Fleming wrote scathing letters to several editors complaining about De Forest's articles. Fleming was incensed by De Forest's account because he marginalized the Fleming valve as being useful only for laboratory work, and he failed to mention that Fleming had received a patent on the device for use as a detector in wireless systems. The exchange of letters clarified several important points that De Forest made in his lecture—in particular the source of inspiration for his audion invention. These acrimonious letters appeared on and off in several publications for the next seven years.

Other Relevant Documents

De Forest's patent applications for his two-electrode flame and evacuated bulb detectors are relevant to his accounts because they provide the only documentary evidence of what he developed and when he developed it. There were four patent applications for a Hertzian wave detector that he filed before the account he gave at his lecture to the AIEE in October 1906. Two of these patents were for flame detectors, which he later claimed were "flame audions," and two were for evacuated bulb audion detectors (see Table 3). Notably, De Forest did not

Table 3. De Forest's flame and audion patents relevant to his accounts of how he developed his two-electrode vacuum audions.

Descriptor	Patent No.	Date Filed	Date issued
1st Flame patent	979,275	Feb. 2, 1905	Dec. 20, 1910
2nd Flame patent	824,638	Jan. 20, 1906	Jun. 26, 1906
1st Audion patent	824,637	Jan. 18, 1906	Jun. 26, 1906
2nd Audion patent	841,386	Aug. 27, 1906	Jan. 15, 1907

mention in his 1906 lecture that he had filed patent applications for any of these four detectors.

Several other important documents were the writings of J. J. Thomson on the subject of currents flowing through gases. De Forest would later claim that he used Thomson's writings as a reference during the time he developed his audion. In an article published by De Forest in 1947, he wrote an account of how he had invented the audion that included this sentence: "Through all this work, the writings of J. J. Thomson were my bible—and constantly were consulted."[11] The most important book that he consulted was the 1903 edition of a textbook by J. J. Thomson entitled *Conduction of Electricity Through Gases*, which first appeared on the market in November 1903.[12] Another important book by Thomson entitled *The Discharge of Electricity Through Gases* was published earlier in 1898.[13]

Not addressed here are the many individual accounts that De Forest published in the thirty years between his Franklin Institute lecture in 1920 and the publication of his autobiography in 1950. While there were many minor differences in these later accounts, they were generally consistent with the account he gave in his 1920 lecture.

Paper Organization

The remainder of this paper is divided into three major divisions, one for each of the three most important accounts that were published in the years 1906, 1916, and 1920:

1. De Forest's AIEE Lecture Account (October 26, 1906)
2. Judge Mayer's Opinion in Marconi v. De Forest Trial (September 20, 1916)
3. De Forest's Franklin Institute Lecture Account (January 15, 1920)

Significant excerpts from the paper that documented his AIEE lecture were soon published in many prominent electrical and scientific journals. As a result, there were many acrimonious exchanges of letters between De Forest and Fleming that were published in several prominent electrical journals for years after the lecture. Judge Mayer's opinion published in the *Federal Reporter* in 1916 summarized some of De Forest's most relevant testimony and also provided some legal insights. The account De Forest gave in his 1920 lecture at the Franklin Institute was very different from both the account at his lecture to the AIEE in 1906 and the account based on his testimony documented at the 1916 trial. The account from the lecture at the Franklin Institute must have been De Forest's favorite because that was the account that he included in an appendix to his autobiography published in 1950.

De Forest's AIEE Lecture Account (October 26, 1906)

Overview of De Forest's AIEE Lecture

De Forest's AIEE lecture, which focused entirely on his two-electrode audion and flame detectors, was his most comprehensive account of the genesis of his two-electrode audions. For purposes of this presentation, the published version of his lecture can be conveniently separated into three parts. The first part consisted of six pages in which he gave two distinctly different and conflicting versions of how he discovered his flame detector. The first version was an experiment in which he inserted two electrodes into the mantel fabric of a Welsbach lamp that he had soaked in an alkaline salt solution to increase the conductivity of the flame. The second version was an experiment in which he inserted two electrodes directly into the flame of a Bunsen burner, one of which was a trough electrode holding an alkaline salt that was placed directly into the hottest part of the flame. After introducing the second version of his flame detector, he gave a dissertation on how this flame detector worked using an I-V characteristic curve that he inferred was generated by his flame detector. In a bizarre twist, the I-V characteristic curve he presented turned out to be from an obscure experiment disclosed by Egon von Schweidler in a lecture entitled "On the Photoelectric Phenomena." This experiment, designed to investigate the photoelectric effect using an evacuated cavity without a flame, will be described in due course. Apparently, De Forest did not realize that the curve was not generated in a flame experiment.

The second part of his AIEE lecture, also consisting of six pages, consisted of an account of the genesis of a new vacuum bulb audion detector. However, instead of introducing the original version of his audion that appeared in his first audion patent application filed on January 18, 1906, he introduced a new configuration that he documented in his second patent application filed on August 27, 1906, just two months before his lecture. De Forest claimed that the genesis of this audion was a configuration that appeared in a paper published by German scientists Julius Elster and Hans Geitel in 1882. To support his claim, De Forest compared his audion configuration to the Elster and Geitel configuration that he claimed he reproduced from their paper. It turns out that the actual configuration in the Elster and Geitel paper De Forest referenced did not match the audion configuration he presented in his paper. To hide that fact, De Forest purposely mislead the AIEE audience by altering the actual Elster and Geitel configuration in three significant ways to make their configuration conform to his preconceived version of the audion.

It is now clear that the genesis of De Forest's audion was not the Elster and Geitel paper, as he asserted. De Forest's wholesale deception has never been documented, not even by John Fleming in his classic book published in 1919 in which he recounted the many issues associated with De Forest's AIEE lecture.[14] It is notable that De Forest retroactively characterized all of his audions as "flame audions," although in his AIEE lecture, he never asserted that the genesis of his evacuated bulb audion was a flame detector. That claim would arise in 1916 as a defense in the lawsuit brought by the Marconi Company claiming that all of De Forest's audions infringed on the Fleming patent.

In the third and longest part of his AIEE lecture consisting of 16 pages, De Forest attempted to describe the theory of how his evacuated audion bulb worked. He began with this statement: "In framing any theory of the action of electric oscillations in the audion a variety of complex, contrary, contradictory phenomena are met with, exceedingly puzzling to explain.[15] While his technical account appeared to be insightful, he pieced together paragraphs of his lecture from J. J. Thomson's book, *Conduction of Electricity Through Gases*, by paraphrasing them without much insight. De Forest's relationship to this important book by a Nobel Laureate will be described in due course. In the end, he admitted he did not know how his audion detectors worked: "I have arrived as yet at no completely satisfactory theory as to the exact means by which the high-frequency oscillations affect so markedly the behavior of an ionized gas."[16]

Virtually all of the claims that De Forest made at his AIEE lecture turned out to be false. He eventually abandoned most of the claims he made at the lecture, with the notable exception of the claim that his two-electrode audion was a relay in which the energy from a battery in the plate circuit increased the sensitivity of his audion. He asserted that the use of the battery distinguished his audion from Fleming's valve, which did not use such a battery. He also continued to claim that his audion with a battery in the plate circuit was much more sensitive than Fleming's valve.

The remainder of this section provides the detail needed to support the assertions made in the previous paragraphs. These paragraphs constitute a critical review of each claim that De Forest made in his AIEE lecture for both his flame and evacuated bulb audions. The first three titled paragraphs address accounts associated with his flame detectors while the next four titled paragraphs address accounts associated with his evacuated bulb audion detectors. The results of this assessment are summarized in a section entitled "Takeaway from De Forest's AIEE Lecture."

First Account of the Genesis of De Forest's Flame Detector

De Forest used this introduction in the publication of his AIEE lecture with the following words:

> "The story of the development of a device of a distinctively new order, from its first inception to its practical reality, adds a human interest to its description which is perhaps too often lacking among scientific records. In 1900 when I was beginning experiments on the electrolytic responder, it was my good fortune to have to work upon it at night in my own room, at a table beneath a solitary gas burner with Welsbach mantle. My source of Hertzian waves was the discharge of a small induction coil placed in an opposite corner and set into operation by a key closed by pulling a string."
>
> "For several days I was elated over the tremendously sensitive and altogether novel type of Hertzian-wave responder thus accidentally discovered.... But alas for the over-sanguine spirits of the young investigator!
>
> "I found I had merely discovered an extremely responsive form of the sensitive gas-flame, and that a bunch

> of jangling keys or a smart clapping of the hands were almost as efficient generators [of a response in the lamp] as was my induction coil."[17]

He later provided an image that documented this early observation in an account he prepared for *Radio News* (see Fig. 3).[18] There is documentation in the form of a short item that De Forest published in *Electrical World* on April 12, 1902, which provided an account that was consistent with the account he gave in the AIEE lecture.[19]

De Forest did not say when he first discovered that he could detect Hertzian waves with electrodes inserted in a flame, but in his AIEE lecture, he did say that he began by measuring the conductivity of an incandescent mantle. However, it can be presumed that he had not yet found the electrical response at the time he wrote the magazine article in April 1902:

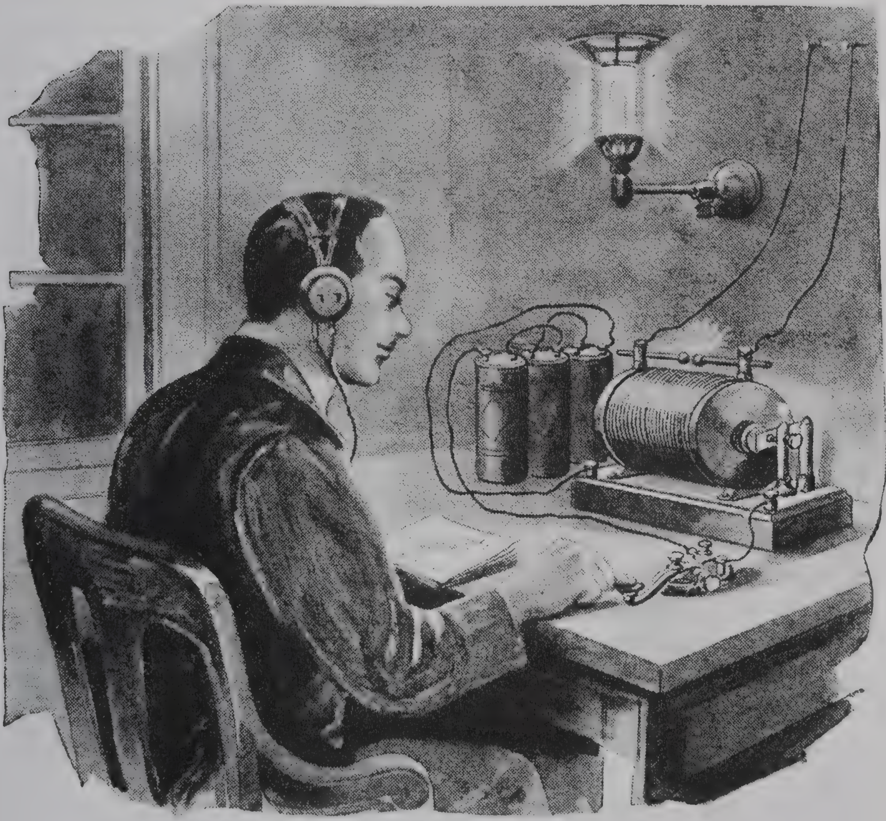


Fig. 3. De Forest published an image memorializing his observation that a spark discharge from his induction coil affected the brilliance of the Welsbach lamp in his room. (*Radio News*, Jan. 1925, p. 1154)

> "Unable to dislodge this conviction from my mind, I began later to search for the genuine response to electric vibration in the gas flame. I found the conductivity of the incandescent mantle surprisingly small for any voltages which would be practical in a wireless receiver."[20]

At some point, De Forest learned that the conductivity of a flame could be greatly enhanced by seeding the flame with various salts, most likely by reading the works of J. J. Thomson entitled *The Discharge of Electricity Through Gases*. Thomson published this textbook in 1898 where he wrote, "When solutions of salts of the metals of the alkali group are thrown into the flame by a spray producer, the conductivity of the flame is very greatly increased."[21] De Forest claimed that the next step in the development of his flame detector was an experiment in which he found the response of electrical signals in the flame of an incandescent mantle that was soaked in alkali salts:

> "By soaking the mantle in a potassium or sodium solution and drying, I was finally able to pass a small current from a dozen dry cells through the flame surrounding it, using two platinum electrodes with a telephone receiver in circuit, and get a faint response to the genuine Hertzian wave. The discovery that the effect predicted was actually present was intensely gratifying."[22]

The statement that De Forest was "intensely gratified" when he first discovered the faint response to Hertzian waves in the mantel of a flame is contrary to all of his later claims. There is no documentation to support this claim, and it is unlikely that soaking a mantle in a potassium or sodium solution (e.g., potassium or sodium chloride) would have any effect on the conductivity of a flame that is contained mainly within the mantle used in a lamp. The mantles of lamps of the day consisted of a fabric bag made from a weave of silk or rayon (see Fig. 4), which was impregnated with metallic salts. For example, Welsbach mantles of the day were impregnated with a mixture of 99% thorium dioxide and 1% cerium dioxide. When a mantle was first ignited (e.g., by a match), the

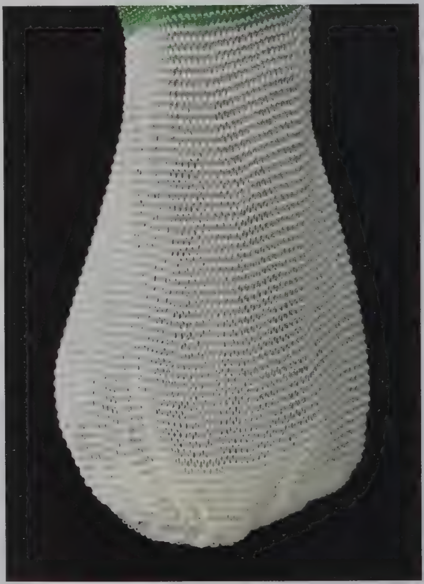


Fig. 4. The mantle of a Welsbach lamp consisted of a fabric bag made from a weave of silk or rayon that was impregnated with metal salts such as a mixture of thorium dioxide and cerium dioxide. (Author's photograph)

fibers that would have absorbed De Forest's salt solutions would have burned away in seconds, and the remaining metallic salts would have formed a rigid but fragile mesh of metal oxides in the shape of the original fabric. It is unlikely that any of De Forest's salts would have been absorbed by the metal oxides that remained. The metallic salts that formed the lattice of the remaining mantle were known to be excellent insulators, even at high temperatures, and it is unlikely that the remaining mantle structure could have contributed to the conductivity flame.

In any event, this claim was in direct conflict with the claim he would make in his lecture at the Franklin Institute in 1920, where he said he did not find a response in an incandescent mantle:

> "For failing to find in an incandescent mantle the genuine effect of response to electrical vibrations I next explored the Bunsen burner flame, using two platinum electrodes held close together in the flame, with an outside circuit containing a battery of some 18 volts and a telephone receiver. See Fig. 1—the form used in 1903."[23]

It will be shown in due course that the "Fig. 1" he referred to above in his 1920 lecture at the Franklin Institute happens to be the same configuration that appeared as Fig. 1 in the patent application for his first flame detector that he filed on February 2, 1905 (see Fig. 5). This flame detector has two electrodes that are inserted on opposite sides of the flame without a mantle (see Fig. 6).

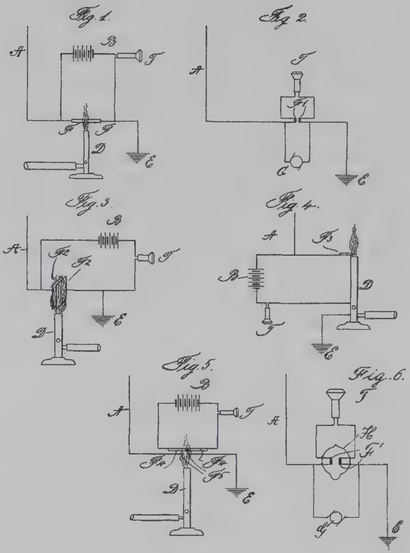


Fig. 5. De Forest filed a patent application for U.S. Patent 979,275 on February 2, 1905, that described images for four different flame detector configurations and two different arc detector configurations. (U.S. Patent 979,275)

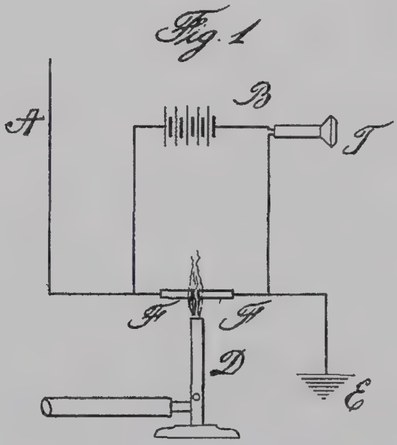


Fig. 6. In De Forest's lecture to the Franklin Institute in 1920, he identified this flame detector from his U.S. Patent 979,275 application as his earliest successful flame detector. (U.S. Patent 979,275, Fig. 1)

Thus, De Forest gave two different and conflicting descriptions of the configuration he used when he discovered that a flame could be used to detect Hertzian waves—the first with a flame contained in a lamp mantle that was pre-soaked in a salt solution, and the second in the open flame of a Bunsen burner, without a mantle, which was seeded with salts in an unspecified manner.

De Forest's Second Account for the Genesis of his Flame Detector

While De Forest claimed that he found the response to electric waves for the first time in an incandescent mantle soaked with salts, he never provided a diagram of the "incandescent mantle" detector, nor did he even describe the configuration. Instead, he introduced a very different version of a flame detector in his lecture, which he claimed was an "early form" of audion (see Fig. 7).[24] It turns out that this "early" form of audion was a later form of an audion flame detector that was first documented in a patent application for U.S. Patent 824,638 that he filed on January 20, 1906 (see Fig. 8).

De Forest did not provide any evidence that this was an early form of audion, and he would never again claim this detector configuration was an early form—with one exception. In March 1919 De Forest wrote an article exclusively for the *Electrical Experimenter* entitled "How I Invented the Audion" in which he included the flame configuration shown in Fig. 9.[25] De Forest doubled down with his caption by claiming it was "The First State in the Development of the Audion by Dr. Lee De Forest." This figure is the same one he introduced in his AIEE lecture as being his early form of audion. He correctly identified this configuration as being documented in his application for U.S. Patent 824,638 dating to January 20, 1906. However,

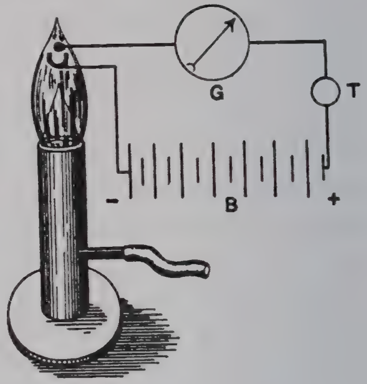


Fig. 7. De Forest introduced this version of a flame detector in his lecture as an "early form" of audion. (AIEE Lecture, p. 721)

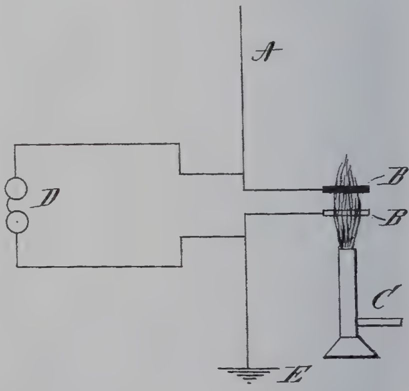
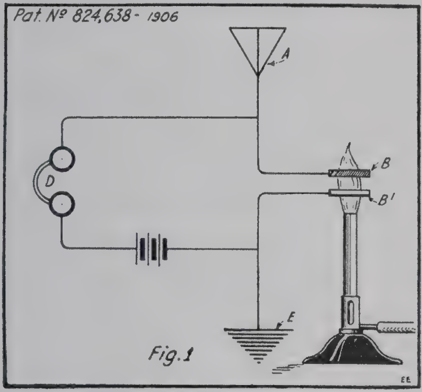


Fig. 8. The first time that De Forest ever documented a two-electrode flame detector with one electrode situated over a second electrode was in the form shown, which first appeared in a late patent application he filed for U.S. patent 824,638 on January 20, 1906, two days after he filed his first audion bulb patent. (De Forest U.S. Patent 824,638, Fig. 1)

De Forest was addled when he wrote this account because he also wrote the following paragraph in the text that referred to this figure:

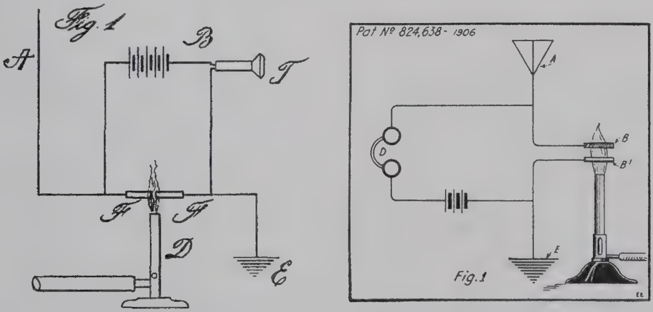


The First State in the Development of the Audion by Dr. Lee de Forest. The Aerial and Ground Were Connected to Two Electrodes Placed in the Flame of a Bunsen Burner, with Successful Results.

Fig. 9. De Forest doubled down on his claim that the flame detector shown in Fig. 7 was an early form with his caption that stated: "The First State in the Development of the Audion by Dr. De Forest." (*Electrical Experimenter*, Vol. 6, Mar. 1919, p. 790)

> "I then investigated the flame of a Bunsen burner and soon found a point *in the outside envelope of the flame* [emphasis added] where an appreciable current did pass between the two electrodes, making a soft fluttering sound in the telephone receiver. (See Fig. 1, Patent No. 824,638, issued in 1906.)" [The parenthetical statement at the end was De Forest's.]

He claimed that he found a point "in the outside envelope of the flame" where an appreciable current flowed between the electrodes, but the figure shows two electrodes inserted across the entire flame at the hottest point of the flame with one electrode situated over the other. He confused the configuration of Fig. 1 in this article with the configuration labeled "Fig. 1" from his flame detector application dating to February 2, 1905 (see Fig. 10). These two configurations appear to be very similar but there was a very important difference. The configuration



Symmetric Flame Audion
Dating to 1905

Asymmetric Flame Audion
Dating to 1906

Fig. 10. The flame detector that De Forest described in his earliest flame detector patent (left) was characterized as "symmetric" because identical electrodes were inserted symmetrically on opposite sides of the flame, whereas the flame detector he introduced in his AIEE lecture (right) was characterized as "asymmetric" because the two electrodes had a different size and shape and they were inserted asymmetrically into the flame. (Author's aggregation of Fig. 6 and Fig. 9)

on the left, taken from his earlier flame patent application, has two identical electrodes inserted symmetrically in the flame. A flame configuration with electrodes inserted symmetrically in the flame was characterized as a "symmetric" flame configuration by early flame researchers. The configuration on the right, introduced in his AIEE lecture, has two very different electrodes that were inserted in the flame with one electrode situated over the other. This configuration with asymmetric electrodes was characterized by early flame researchers as an "asymmetric" configuration.

It turns out that some early researchers studying flame conductivity found that the measured current of a symmetric flame configuration was virtually identical when the polarity of the battery used to make the measurements were reversed. The experimental results obtained by Arthur Smithells, Harry Dawson, and Harold Wilson in 1899 will be presented in due course. They also found that the current measured for an asymmetric flame configuration was not the same when the batteries were reversed. The asymmetric conductivity displayed by a two-electrode configuration was and still is characterized as being unilateral, or unipolar. It will be shown in due course that the I-V characteristics of the flame and evacuated bulb detectors are the key to understanding the response of both, and it is also the key to determining that the physics of the flame detector is different from the physics of the evacuated bulb detector.

By 1906, De Forest was well aware of the difference in the response of a flame detector depending on the degree of symmetry or asymmetry of the electrodes. The following words can be found in his patent application filed in 1906 for the flame detector configuration he presented at the AIEE:

> "If both electrodes are of the same material, they should preferably be of different sizes, and if of different materials they may be of the same or different sizes. When said electrodes are heated by the flame from the burner or other source of heated gas, an electromotive force is developed and creates current in the local circuit which includes the telephone or other signal indicating device."[26]

It remains a mystery as to why De Forest chose to represent his late form of the flame detector as the early form in his AIEE lecture when it was not. There are at least three possibilities:

1. The flame detector that he identified in his AIEE lecture turned out to be a more sensitive detector than the earlier version appearing in his 1905 patent application.
2. The asymmetric form he described in his AIEE lecture was more like his vacuum bulb audion than the symmetrically placed electrodes that appeared in his 1905 flame patent.
3. The experimental data available on the physics and chemistry of the conductivity of flames in the day was generally obtained by researchers using asymmetric configurations with one electrode situated over the

other; no examples of data on De Forest's symmetric flame configuration could be found in the literature.

De Forest Presents the I-V Characteristic Curve for his Flame Detector

De Forest opened his dissertation on the flame detector he featured in his AIEE lecture as being remarkably sensitive to weak high-frequency oscillations. He stated that the current flowing between the two electrodes of this flame detector did not increase linearly with applied voltage and the conductivity of the flame did not follow Ohm's law:

> "It was observed that the increase of current with electromotive force did not follow ohms law; a saturation value of the current was observed. Wilson found that the maximum [i. e., saturation] current with salt vapor in a flame can carry is equal to the current which if passed through an aqueous solution of that salt would electrolyze the same quantity of the salt as was imparted during the same unit of time to the heated gas.
>
> "Beyond this saturation value the current will not rise until the electromotive force is great enough to enable the field itself to ionize the gas; that is, until the velocity imparted to the negative ions by the field is sufficient to enable them to separate the gas molecules with which they collide into positive and negative ions."[27]

This statement was accompanied by an I-V characteristic curve of unspecified origin (see Fig. 11). De Forest provided no references for this figure, so the only clue to its origin was the reference in the previous paragraphs to an anonymous person named Wilson.

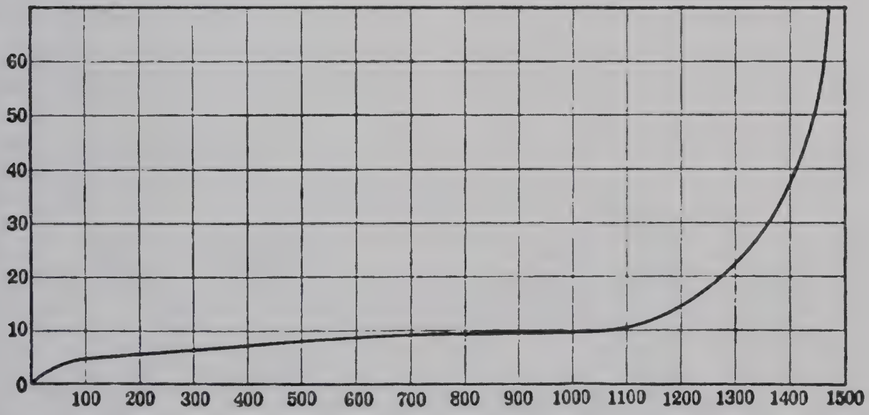


Fig. 11. De Forest claimed this I-V curve was from a flame experiment when in fact it was from an experiment by Egon von Schweidler in 1899 using a cylindrical chamber containing an adjustable plate located approximately 3 to 5 mm from the wall of the chamber, which was evacuated to an air pressure of one-sixth of an atmosphere without a flame or heated electrode. (AIEE lecture, p. 721)

Who is Wilson?

The index of Thomson's book, *Conduction of Electricity Through Gases*, listed two Wilsons, one with initial C.T.R and the other with initials H. A. It turned out that Harold A. Wilson had published many papers on the subject of conductivity of flames. However, a thorough search of Wilson's papers published before 1907 did not reveal an I-V characteristic curve that looked anything like the one in this figure.

It also turned out that the introductory paragraph cited above was a paraphrased version of a paragraph that appeared on page 210 of Thomson's book, *Conduction of Electricity Through Gases*:

> "Wilson measured this limiting current and found that it was equal to the current which when passing through an aqueous solution of the salt would electrolyze in one second the same quantity of salt as was sprayed in that time into the hot air."[28]

This confirmed suspicions that De Forest was paraphrasing Thomson's book when he described the physics of the conductivity flames. This prompted a page-by-page search of Thomson's book to see if he had referenced the source of this I-V curve. A search of his book not only revealed a citation to this figure, but it also revealed the actual curve shown here was copied from page 13 in a section dealing with the conductivity of gases between parallel plates.

Thomson stated that this curve was generated by measuring the current through the gas at reduced atmospheric pressure contained between two parallel plates exposed to "some ionizing agent," in this case the ionizing agent was an arc lamp that liberated electrons from the surface of a solid by the photoelectric effect, not heating. Thomson also gave the original reference for this I-V curve as being an experiment by one Egon von Schweidler that was first published in 1899.[29] Egon von Schweidler disclosed this figure in a lecture entitled "On the Photoelectric Phenomena" (see Fig. 12),[30] which he gave at the University of Vienna on February 16, 1899. The horizontal scale

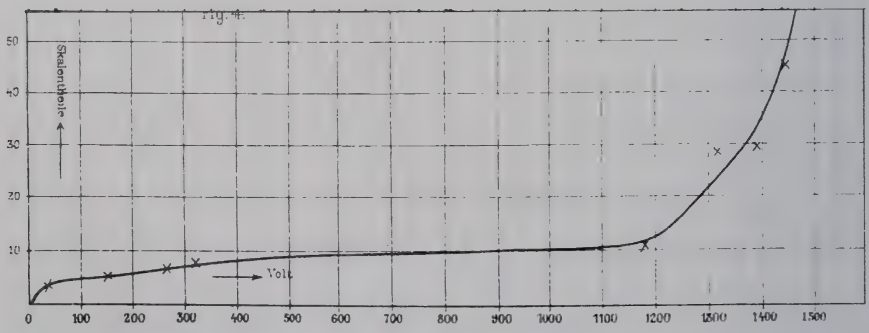


Fig. 12. According to J. J. Thomson, the I-V characteristic curve of Fig. 11 was reproduced from this original curve that Egon von Schweidler generated and published in 1899. (E. Von Schweidler, *Wien. Bricht*, Vol. 108, 1899, p. 280)

is "volts" and the vertical scale is "skalentheile" or "scale divisions," meaning the scale is relative, not in units of current.

The experimental apparatus von Schweidler used to generate this curve was a small cylindrical vacuum chamber with a plate attached to a rod used to adjust the position of the plate with respect to a screen mesh located behind a transparent window (see Fig. 13).[31] To generate this curve, the plate was set at a distance of 3 to 5 mm from the conducting mesh and the atmospheric pressure in the chamber was set at approximately 130 mm. The source of ionizing radiation was an arc lamp that ionized atoms at the surface of the plate and ejected them from the surface via the photoelectric effect. Von Schweidler generated the I-V curve by measuring the current as the arc lamp output was increased until the electric field across the plates reached the breakdown threshold of air. The resulting breakdown voltage shown in the von Schweidler figure is approximately 1,500 volts, which translates into an electric field of 300–500 kV/m for a spacing of 3 to 5 mm—a reasonable breakdown threshold for air at a pressure of 130 mm, approximately one-sixth of an atmosphere.

This curve has nothing to do with a flame configuration or an experiment with heated electrodes or even an experiment at atmospheric pressure. It was amusing to read the next few pages of De Forest's paper, where he waxed eloquently about the physics behind his flame detector using an experimental curve that was generated by using an evacuated cavity in which the chamber was exposed to the light of an arc lamp to ionize gas from one surface of the two parallel plates by means of the photoelectric effect. The best part is where De Forest explains why the electrode containing the salt must be incandescent to produce this curve: "The conduction through flames under the conditions I am describing is due chiefly to the negative ions generated, and these are chiefly in the vicinity of the metallic cathode. It is necessary that the alkali vapor comes in contact with the glowing metal." There

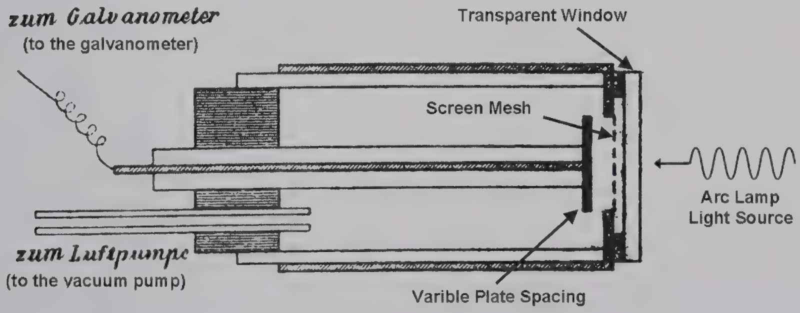


Fig. 13. The experimental apparatus von Schweidler used to generate this curve was a small cylindrical vacuum chamber with a plate attached to a rod used to adjust the position of the plate with respect to a screen mesh located behind a transparent window. (E. Von Schweidler, *Wien. Bricht*, Vol. 108, 1899, p. 274)

are no electrodes heated to incandescence in this experiment, and the "negative ions" are electrons that are liberated (ionized) from one surface of a cavity by the photoelectric effect, not by heating. Also, the gas is at a pressure of one-sixth of an atmosphere.

De Forest's use of this I-V characteristic curve that was not derived from a flame to explain the operation of his flame detector is nothing short of bizarre. Either De Forest used this curve knowing that it did not apply to a flame, or he failed to understand the text in Thomson's book on the page where this figure was located. Either way, it shows an incredible amount of deception or ignorance. It is also obvious that De Forest did not realize that measurements using both positive and negative voltages were required to generate a complete characteristic curve for a detector of oscillations that had both positive and negative swings.

One might ask why De Forest did not measure the I-V characteristic curve for his flame detector rather than going through the charade of using a characteristic curve having nothing to do with a flame. It turns out that it is not easy to make conductivity measurements of a flame detector that is seeded with alkali salts to enhance the conductivity. Wilson reported that the currents produced in the electrodes he used to measure the I-V characteristics of his flame configurations required the use of a Kelvin galvanometer with a sensitivity threshold of 10^{-9} amperes.[32]

Worse yet, the injection of salts into the flame to increase conductivity was problematic. In their seminal 1899 paper, authors Arthur Smithells, Harry Dawson, and Harold Wilson wrote:

> "It was found that any unsteadiness of the flame produced considerable and irregular deflections of the galvanometer which prevented the current from being measured in a satisfactory manner."
>
> "With a view to reducing this oscillation to a minimum, so as to obtain a steady galvanometer deflection, care was taken to regulate the quantity and pressure of the gas and air supplies with as much nicety as possible."[33]

Wilson used exceedingly complex equipment to measure the I-V characteristic curves of flames seeded with salts. One example of the equipment he used consisted of two different apparatuses, one used to measure the I-V characteristics, and the other used to generate a controlled flow of a mixture of gas, air, and a salt solution that was injected into the bottom of the burner barrel to produce a very stable flame and a measurable concentration of a salt solution.[34] The apparatus used to measure the I-V characteristics with two disk electrodes inserted into the flame, one above the other, is shown in Fig. 14. Both disk electrodes had diameters sufficient to extend across the entire cross-section of the flame. The lower disk consisted of a mesh with a spacing that allowed the flame to reach the upper electrode. The arrow at the bottom of the figure indicates where the controlled mixture of gas, air, and salt solution entered the burner barrel.

The apparatus that generated this steady flow of the mixture was much more complex than the measurement apparatus itself (see Fig. 15). No attempt will be made to describe the details of either apparatus. The point of this discussion is to show that De Forest did not do what was required to stabilize the flame or to ensure the uniformity of the salt concentration between the electrodes of a flame, both of which were needed to properly measure the complete I-V characteristic curve that included both polarities of applied voltage.

The three methods that De Forest mentioned for seeding his flame with salts were crude by comparison: 1) a spray of a salts solution into the flame with an

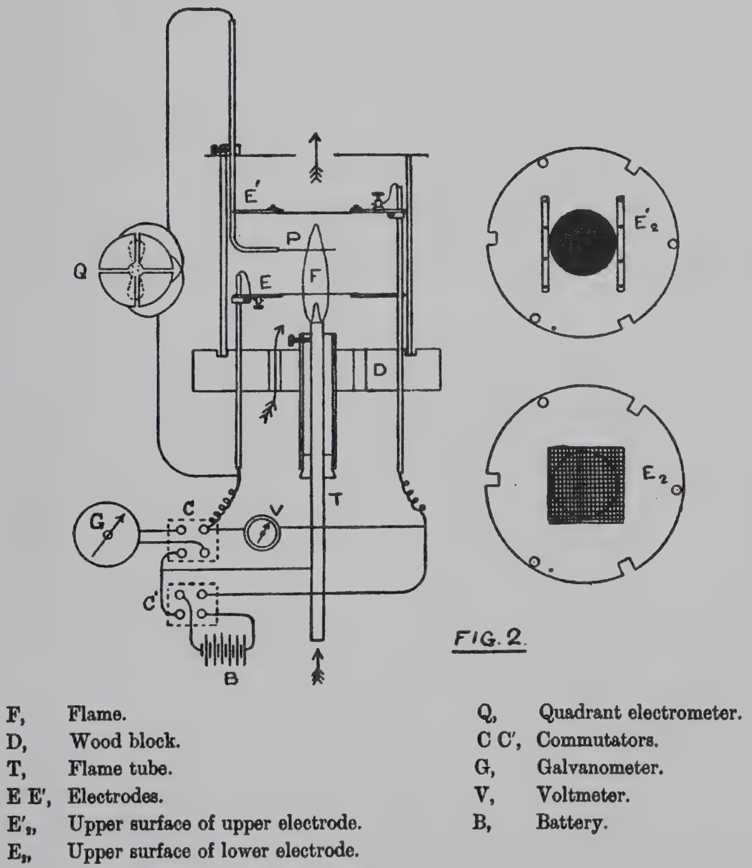


Fig. 14. Wilson used this complex apparatus to measure the I-V characteristics of a flame seeded with alkali salts using two disk electrodes inserted into the flame, one above the other; the arrow at the bottom of this figure indicates where a steady flow of gas mixed with a salt solution was inserted into the bottom of the burner barrel. (Wilson, *Trans. Royal Society of London*, Vol. 192, Apr. 27, 1899, p. 502)

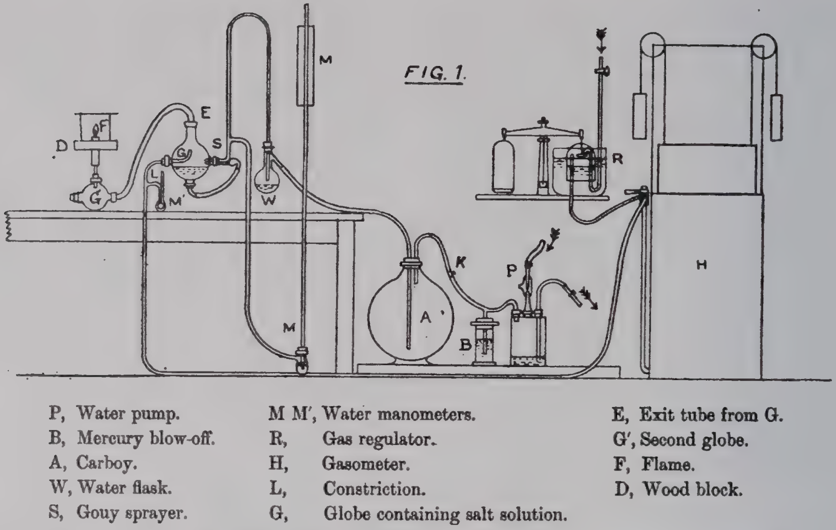


Fig. 15. Wilson used this complex apparatus to generate a steady and measurable flow of gas, air, and salt solution for injection into the bottom of the burner barrel shown in the previous figure. (Wilson, *Trans. Royal Society of London*, Vol. 192, Apr. 27, 1899, p. 500)

atomizer, 2) a trough (with dimensions of 2 mm by 1 cm) situated at the end of an electrode inserted into the flame to hold salts, and 3) a coating on the cathode electrode with a salt solution. It is difficult to imagine how any of De Forest's methods would have produced the steady flame with a constant level of salt seeding over the time needed to measure the I-V characteristic using both battery polarities.

The Unipolar Response of Flames

Even more important than what De Forest said about the I-V characteristic curve of his flame detector was what he did not say. By 1906 it was well known that the measured current flowing between two electrodes inserted into a flame had what was known as a "unipolar" response, which meant that magnitude of the measured current flowing in a galvanometer was different when the battery terminals connected to the electrodes were reversed without changing the voltage. It is difficult to understand how he could have missed that point. De Forest claimed he often read J. J. Thomson's 1903 book during the time he developed his audion. Here is what Thomson wrote in this book:

> "The current is proportional to the velocity of the ion which carries it; thus since the velocity of the negative ion is greater than that of the positive, the current for the same difference of potential between the plates [i.e., electrodes] is greater when the ionization takes place next the negative plate than when next the positive, in other words the current is greater in one direction

> than in the opposite; this unipolar conductivity as it is called is very marked indeed in conduction through hot gases and flames containing salts."[35]

If De Forest had read any of the papers in the literature describing the conductivity of flames seeded with salts he would have found virtually all of these papers had data that specifically showed the conductivity of salted flames was found to be unipolar. The characteristic curve for a flame experiment that appeared in a paper published by Smithells, Dawson, and Wilson is an excellent example of how the I-V characteristics of a flame with a unipolar response were displayed (see Fig. 16).[36] They graphed their data using only two of the four quadrants that are formed by the combination of positive and negative current axes with positive and negative voltage axes. At first glance, it might appear that the curves show results for only one polarity of applied voltage. However, the upper curve would appear in the upper right quadrant of a four-quadrant graphical representation, and the lower curve would appear in the lower left and upper left quadrants. No part of this curve would have appeared in the lower right quadrant.

This is not the same format that electrical engineers of the day used for the I-V characteristics of crystal detectors. They generally plotted the curves graphically by displaying all four quadrants. Twelve years after this figure was

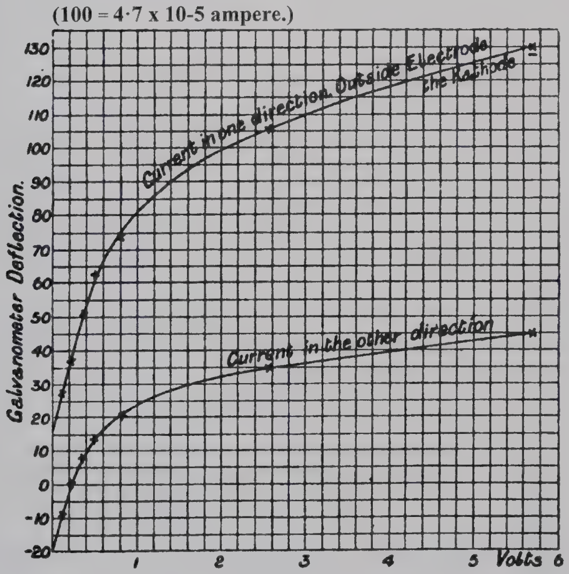


Fig. 16. The I-V characteristics for flames reported by Wilson and his colleagues exhibited a significant unipolar response such as the one shown in this curve where a reversal of battery polarity resulted in a large change in the magnitude of the measured current. (A. Smithells, et al., *Phil. Trans.*, Vol. 193, 1899, p. 99)

published, Wilson wrote a book in which he replotted the curves from this figure using all four quadrants (see Fig. 17).[37] This form of the I-V curve, which most radio engineers are familiar with today, clearly shows the unipolar nature of this particular flame detector. For example, a positive voltage of two volts produced a current with a magnitude of 100 units (4.7 × 10^{-7} amperes), while the same voltage with the polarity of the battery reversed produced a current with a magnitude of about 35 units. Thus, a change in polarity without a change in voltage produced a difference in current amounting to a factor of three.

It does not necessarily follow that the flame detector De Forest presented at the AIEE lecture also had such a unipolar response. For example, if two identical electrodes are inserted symmetrically into a flame and the flame is also symmetric, a change in polarity of the battery attached to the two electrodes would not change the magnitude of the resulting response. Wilson must have followed this line of reasoning when he designed an experiment to measure the asymmetry of a configuration that had a symmetric placement of electrodes. Wilson's description of this experiment was very brief: "The electrodes consisted of two platinum plates equal in size and placed as symmetrically as possible in the flame. A ¹⁄₁₆ normal solution of KCl was used in these experiments."[38] The results were entered into a table, which indeed revealed a relatively small unipolar response for voltages between 1.5 and 43.5 volts (see Table 4). The difference in the magnitude of the current measured due to a change in battery

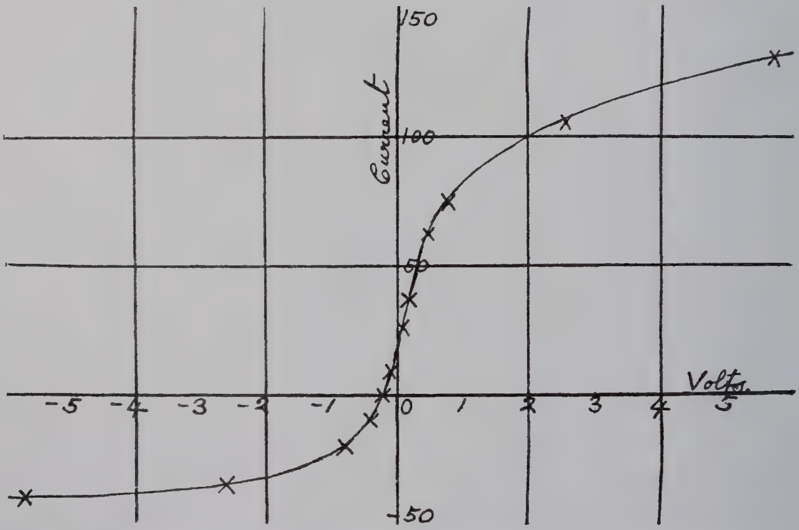


Fig. 17. Wilson replotted the I-V characteristic curve pictured in the previous figure using all four quadrants of the two variables (voltage and current); this form of the curve clearly shows a unipolar response. (Wilson, *The Electrical Properties of Flames and of Incandescent Solids*, 1912, p. 76)

Table 4. H. A. Wilson's I-V characteristic data measured with electrodes inserted symmetrically into the flame.

E.M.F. in volts	Galvanometer deflection	Galvanometer deflection (current reversed)
43.5	+39.7	- 48.8
29.0	+33.2	- 41.0
14.5	+24.7	- 29.3
7.3	+19.4	- 23.0
2.9	+15.1	- 16.9
1.5	+12.8	- 14.2

polarity was only 10% at 1.5 volts and it rose steadily to 20% at 43.5 volts. Wilson correctly concluded that electrodes inserted symmetrically into a flame produced symmetric I-V characteristics and asymmetric electrodes resulted in an asymmetric, or unipolar I-V characteristic curve.

Another important point is that none of the I-V characteristics for seeded flames published in the literature displayed a valve effect in which the current for only one polarity was essentially zero over a wide range of applied voltages useful in radiotelegraphy. This is no surprise because the currents in the seeded flames for both battery polarities were a result of the ionized gas between the electrodes. The currents were different because of the difference in the mass of the positive ion and the electron, but in neither case were the currents even close to zero. The flow of current in both directions in a flame distinguishes the response of a flame detector from the response of an evacuated bulb detector with one highly incandescent electrode—which displays not only a unipolar response but also a valve effect.

Returning to the discussion of the I-V curve that De Forest presented at his AIEE lecture, it turns out that the flame detector he described was highly asymmetric:

> "The size and shape of the electrodes are of small moment. I prefer a trough anode 1 cm long by 2 mm wide, holding the potassium salt, as [the] cathode, and a small platinum wire parallel thereto and held 2 to 10 mm above it as [the] anode. The trough electrode should preferably be at the upper tip of the oxidizing flame at its junction with the reducing flame. When this is made negative the current is saturated with a comparatively small potential difference."

Because his flame detector was highly asymmetric it would have exhibited an asymmetric I-V curve similar to the one that appears in Fig. 17. By using a characteristic curve that did not apply to a flame, De Forest missed the fact that the flame detector he presented at his lecture should have exhibited unipolar a response. In doing so, he would have also missed the fact that there would have been two points on his characteristic curve with rapid changes in current where the detector was most sensitive—not just the one he showed in his AIEE lecture.

Genesis of De Forest's Vacuum Bulb Audion Detector

De Forest claimed the genesis of his vacuum bulb audion was an article written by Elster and Geitel in 1882. De Forest opened his discussion on his vacuum bulb audion by citing their paper in an issue of Wiedemann's *Annalen der Physik* dating to 1882:

> "Elster and Geitel,* beginning in 1882 a systematic investigation of the ionization produced by incandescent metals, frequently employed an exhausted glass vessel containing an insulated platinum plate, stretched close to which passes a fine metallic filament brought to incandescence by an electric current."
>
> "*Elster and Geitel, *Wied. Ann.*, xvi, 1882."[39]

He presented an image of what he claimed to be the experimental configuration from the Elster and Geitel publication (see Fig. 18). Using this image, De Forest then went on describe what Elster and Geitel found:

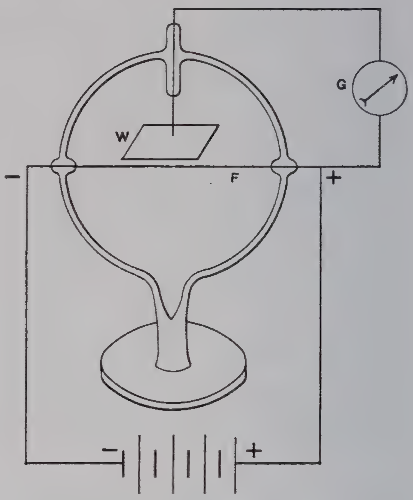
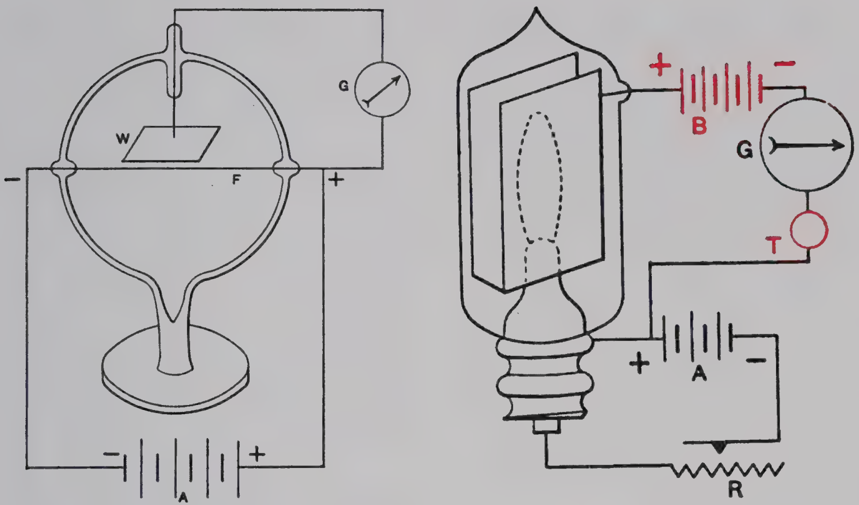


Fig. 18. De Forest represented this figure as being the experimental configuration that Elster and Geitel used in 1882 to demonstrate "the remarkable unidirectional quality of a gas at low pressure when the cathode is an incandescent wire or filament, and illustrated the exact device employed subsequently by Prof. Fleming and myself." (AIEE lecture, p. 725)

> "If the metal plate be connected by an outside wire to the positive terminal of the hot filament, a leak-current from the plate to the filament through the gas will be set up, as Elster and Geitel first found, passing mainly to that portion of the filament near its negative terminal. If the resistance of the lamp filament and the lamp's voltage be high, a very considerable leak current may thus be set up."[40]

De Forest added a battery and a telephone receiver to the Elster and Geitel configuration (see Fig. 19), and he claimed that the saturation (maximum) current in the plate circuit of this vacuum bulb increased rapidly as the temperature of the wire was raised by increasing the current in the filament:



a) De Forest's representation of Elster & Geitel's configuration

b) De Forest's representation of his audion with a battery and telephone

Fig. 19. De Forest claimed that Elster and Geitel's configuration on the left was the genesis of his audion bulb detector, which he invented by adding a battery and a telephone receiver to their configuration that resulted in the audion configuration on the right. (AIEE lecture, p. 727)

> "A battery of from 3 to 18 dry cells is connected between the positive end of the filament and the platinum plate *w*, the latter being connected to the positive pole. The saturation current increases rapidly with the heating current through the filament, which also increases the velocity of the negative ions, as does also an increase in the applied electromotive force between plate and filament."

It is important to note that De Forest used the generally accepted convention that the long line of a battery in a schematic diagram represented the positive terminal and the short line represented the negative terminal. Thus, the positive terminal of the battery in the plate circuit was connected to the cold plate, and the negative terminal of the plate battery was connected to the positive terminal of the filament battery. He reinforced this by placing the positive and negative symbols appropriately.

De Forest then concluded that the external battery made his device much more sensitive than the device in Fleming's patent, which did not have a battery in the plate circuit:

> "Fleming points out that when the cold plate of the Elster-Geitel tube is connected to the positive end of the filament, and the two put in a high-frequency oscillation circuit, only the positive half of the oscillation can pass from the plate to the filament across the gas. He uses this principle to rectify the Hertzian oscillations, and applies the

> unidirectional currents of the oscillations themselves to operate a sensitive galvanometer, or direct current instrument, for quantitative measurements over very short distances. When an independent external source of electromotive force is applied, in the manner I have described, the action becomes quite different. It then operates as a *relay* to the Hertzian energy instead of merely rectifying this energy so that it can be used directly to give the sense signal. The Audion therefore is tremendously more sensitive and available in practical wireless."[41]

While De Forest's statement implied that the genesis of his audion invention was the Elster and Geitel experiment, he did not explicitly make that claim in his AIEE lecture. However, he did make an explicit claim in response to a letter that Fleming wrote to *The Electrician* after reading the above paragraph that was published in an earlier issue of *The Electrician* dated November 23, 1906.[42] Fleming was incensed by the above paragraph in his paper and responded with a letter of his own to the editor of *The Electrician*, which appeared in the next issue dated November 30, 1906. Fleming scolded De Forest in his letter and corrected him by stating that he (Fleming) had discovered his valve as a result of studying the Edison effect in 1890, not from the Elster and Geitel experiment in 1882:

> "As far back as 1890, when investigating the so-called 'Edison effect' in glow lamps, I discovered the unilateral conductivity of the space between the incandescent filament and a cold metal plate held on a platinum wire sealed through the glass, and in November, 1904, discovered that this unilateral conductivity held good for high frequency currents.... and described the use of this device as a receiver in connection with electric wave telegraphy...."[43]

De Forest responded to Fleming with a letter that appeared in an issue of *The Electrician* dated December 12, 1906.[44] In this letter he explicitly stated that the Elster and Geitel experiment was the genesis of his audion:

> "Sir: In reply to a letter appearing in your recent issue by Prof. Fleming, I will say that not only in my original paper before the American Institute of Electrical Engineers, but also in the abstract printed in *The Electrician*, it is seen that I mention not only the device described by Prof. Fleming in 1904, but point out the real genesis of this device by Elster and Geitel in 1882, or eight years prior to its 're-discovery' by Prof. Fleming in 1890. The German investigators were at that early date demonstrating the remarkable unidirectional quality of a gas at low pressure when the cathode is an incandescent wire or filament, and illustrated the exact device employed subsequently by Prof. Fleming and myself. However, the figure in the abstract of my paper clearly shows the local battery in the telephone circuit, which makes all the difference between a possible rectifier of alternating current of very considerable voltage

> and a relay or trigger device, whereby the flow of the local current is affected to an extraordinary degree."[45]

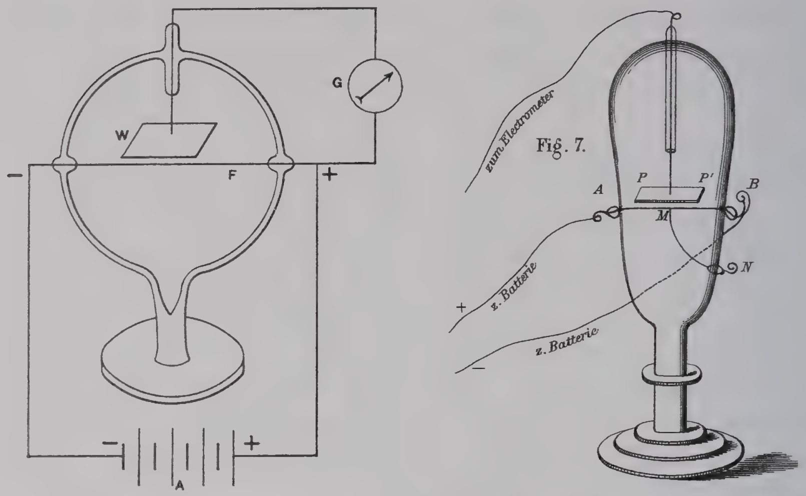
This paragraph constitutes the smoking gun in which De Forest asserted "the real genesis of this device was by Elster and Geitel in 1882," which he followed by an assertion that they "illustrated the exact device employed subsequently by Prof. Fleming and myself." De Forest then distinguished his invention from Fleming's invention by stating that he had added a local battery to the external circuit of the Elster and Geitel configuration whereas Fleming had not. The conclusion reached here is the same as the conclusion reached by an unnamed editor or correspondent for the *Electrical Age* based on De Forest's lecture:

> "The audion, the wireless receiver which Dr. De Forest described in his recent paper before the American Institute of Electrical Engineers…is printed elsewhere in this issue…. In its present form it appears to be based on the Elster and Geitel tube for showing the ionization of a gas, or the electrification of a platinum plate using an incandescent filament, which device, as Dr. De Forest points out in his paper, Fleming has used for rectification of Hertzian oscillations…. De Forest adds the external electromotive force in the flux [i.e., plate] circuit, whereupon, as he states, the audion is born. In his paper, Dr. De Forest expresses the opinion that the addition of the external flux battery causes the audion to act as a relay to the Hertzian remedy."[46]

De Forest Misrepresented the Elster and Geitel Experiment

De Forest claimed that the evacuated audion bulb configuration he presented in his AIEE lecture represented the figure that Elster and Geitel published in their 1882 paper. However, the configuration that Elster and Geitel published in their paper, shown on the right of Fig. 20, was very different from the configuration that De Forest represented as being from their paper, which is shown on the left of this figure. There are three critical differences between the two versions:

Substitution of a Galvanometer for an Electrometer: De Forest replaced the electrometer that appeared in the Elster and Geitel configuration with a galvanometer denoted by "G." An electrometer is a high-impedance measuring device often used to measure the potential difference between two points in a circuit isolated by a high impedance, while a galvanometer is a relatively low-impedance device (on the order of a few thousand ohms or less) often used to measure a current flowing in a circuit. De Forest claimed that Elster and Geitel measured currents: "If the metal plate be connected by an outside wire to the positive terminal of the hot filament, a leak-current from the plate to the filament through the gas will be set up, as Elster and Geitel first found, passing mainly to that portion of the filament near its negative terminal."[47] If De Forest had read Elster and Geitel's paper he would have found tables of voltage measurements associated with this figure, not current measurements. During another part of his discourse on the



DE FOREST DRAWING

ELSTER & GEITEL DRAWING

Fig. 20. The configuration that De Forest represented as being from the Elster and Geitel paper (left) was very different from the configuration that actually appeared in their paper (right). Most importantly, the plate of the Elster and Geitel figure was connected to the horizontal wire at M through an electrometer (not a galvanometer) that was connected to terminal N, not to either battery terminal as indicated in De Forest's circuit. (Left: AIEE lecture, p. 725; Right: *Ann. d. Physik*, Vol. xxxi, 1887, p. 109)

Elster and Geitel experiments, De Forest reported that potential differences were measured with this circuit that he claimed used a galvanometer: "Ordinarily at atmospheric pressures and red heats a positive charge was produced upon the plate, of the order of a few volts."[48] Potential differences between isolated electrodes cannot be measured with a galvanometer.

Missing Wire (MN) to Balance Charge: De Forest's representation of the Elster and Geitel configuration was missing the wire MN that connected the center of the filament wire at M to the terminal N on the outside of the glass, which according to the text of the Elster and Geitel paper was grounded. The purpose of the ground wire was to balance the negative charge on one half of the filament wire AB with the positive charge on the other half of the wire so the net charge on the wire would not influence the potential of the isolated plate as the filament current was increased.

Erroneous Connection of the Plate Circuit to the Filament Battery: In De Forest's configuration the plate circuit was connected to the positive pole of the battery, whereas in the actual Elster and Geitel circuit the plate circuit was connected to one side of an electrometer but does not show where the other terminal of the electrometer is connected. However, the text stated that the other terminal of the electrometer was connected to terminal N. Thus, the plate circuit was actually connected to the center of the horizontal wire by the wire MN, not by connecting the plate circuit to either the battery terminal, as it is in De Forest's circuit.

The circuit that Elster and Geitel used to measure potential differences of isolated electrodes in a flame with an electrometer appeared in a figure from another nonrelated paper they published earlier (see Fig. 21).[49] In this figure, each electrode from the flame is connected to each of the two electrometer terminals through a double-pole double-throw switch. The purpose of the switch was to initialize the electrometer by shorting both the electrometer and the electrodes in the flame to ground to drain off all the charge and set the potential difference of the electrometer input terminals and the two flame electrodes to zero. To make a measurement, the switch was then thrown to connect the two electrodes to the two terminals of the electrometer, one of which remained grounded at the switch to provide a reference electrode for measuring the change in potential of the second electrode.

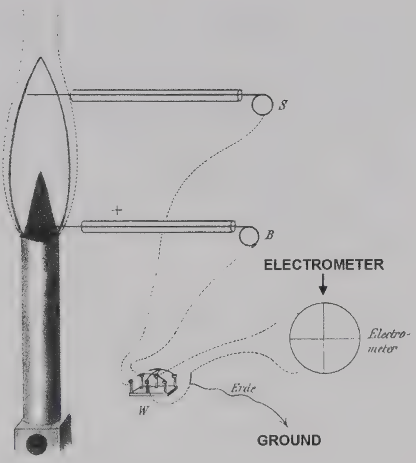


Fig. 21. The circuit that Elster and Geitel used to measure potential differences of isolated electrodes with one grounded electrometer lead appeared in a figure from another unrelated paper that they published earlier where they were measuring the potential difference between two isolated electrodes in a flame. (*Ann. d. Physik*, Vol. 16, 1882, p. 223)

To summarize, De Forest not only replaced the electrometer with a galvanometer, but he eliminated the connecting wire MN and instead showed a connection of the galvanometer to one lead of the battery—specifically to the positive lead of the battery. In doing so he created a deceptive configuration to match the configuration of the audion that he introduced. The configuration that De Forest represented as being the Elster and Geitel configuration was actually identical to the Edison effect bulb configuration that Edison used to measure his Edison effect current. It will be shown in an addendum to Part II that the actual Elster and Geitel configuration shown here was not used by Elster and Geitel to demonstrate the unipolar response of a hot wire in an evacuated chamber. The actual configuration that they documented in their paper for that purpose, which was completely different, will be presented.

De Forest Misrepresented the Publication Date of the Elster and Geitel Paper

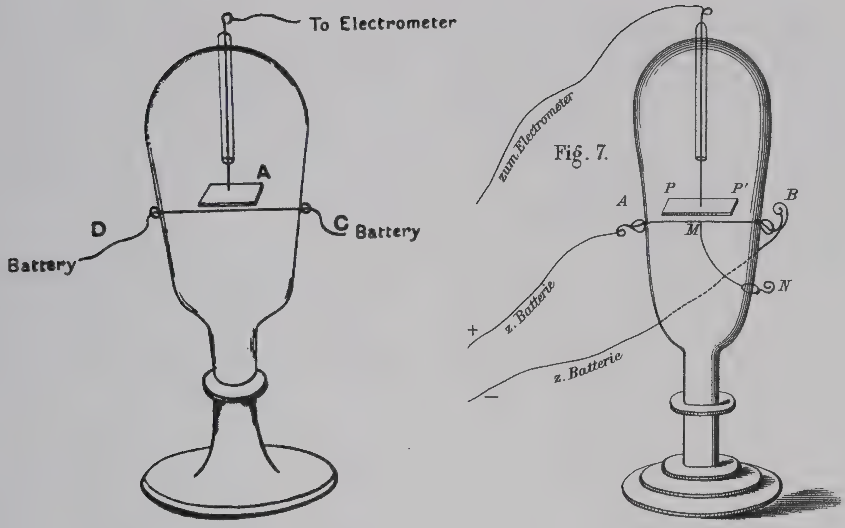
In a letter to the editor of *The Electrician* dated December 29, 1906, Fleming pointed out that the Elster and Geitel configuration to which De Forest had referred in his AIEE lecture was not published in 1882 as he claimed. Fleming claimed the paper to which De Forest had referred was entitled "On the Electricity of Flames." He corrected him by stating that the paper was published in 1887:[50]

> "Sir: In his letter published in your issue of Dec. 28th in reply to mine of Nov. 30th last Dr. De Forest seems to have committed the common mistake of failing to verify his references. If he had consulted the original paper of Elster and Geitel published in *Wiedemann's Annalen* for 1882, to which work he makes reference, he would have seen that its title is 'Ueber die Electricität Flamme,' and that it has nothing whatever in it which anticipates my subsequent invention of an oscillation valve for high-frequency currents.
>
> "It is true that in 1887 they published a paper "Ueber die Electrisirung der Gase durch Glühende Körper," in which an apparatus is described consisting of a glass bulb having a platinum wire electrically heated sealed across it and an insulated plate contained in it."[51]

When De Forest responded to Fleming's letter, he ignored Fleming's objection to the date of the Elster and Geitel paper and continued to maintain as late as 1913 that the date of this Elster and Geitel paper was 1882: "The vacuum valve, as first discovered by Edison and carefully studied by Elster and Geitel* has most marked rectifying properties, excelling in efficiency any electrolytic or crystal rectifier."[52] The asterisk in this sentence referred to a footnote citing the 1882 date: "*Wiedemann's 'Annalen,'* xvi, 1882."

How was it possible that De Forest maintained his position on the erroneous 1882 date long after Fleming corrected him? Fleming suggested that De Forest never actually read the Elster and Geitel paper that he referenced. It turns out that J. J. Thomson reproduced an image of the Elster and Geitel configuration on page 26 of his 1903 book, which De Forest claimed was a bible that he often consulted during this period. This configuration was very similar to the one that appeared in the original Elster and Geitel paper, but there was one significant difference. Thomson deleted the wire MN that connected the center of the wire AB to the external binding post MN, which appeared in the Elster and Geitel paper (see Fig. 22). While Thomson deleted this wire from his figure, he did refer to the existence of this wire in the text where he explained the purpose of the missing wire. Perhaps he deleted the wire so he could more easily describe the purpose of the experiment. While the wire was required for a successful experiment, it did not involve its purpose or contribute to the interpretation of the results:

> "To prevent any disturbing effect arising from the change produced by the current in the electric potential of the wire, the middle point of the wire was connected with the earth."



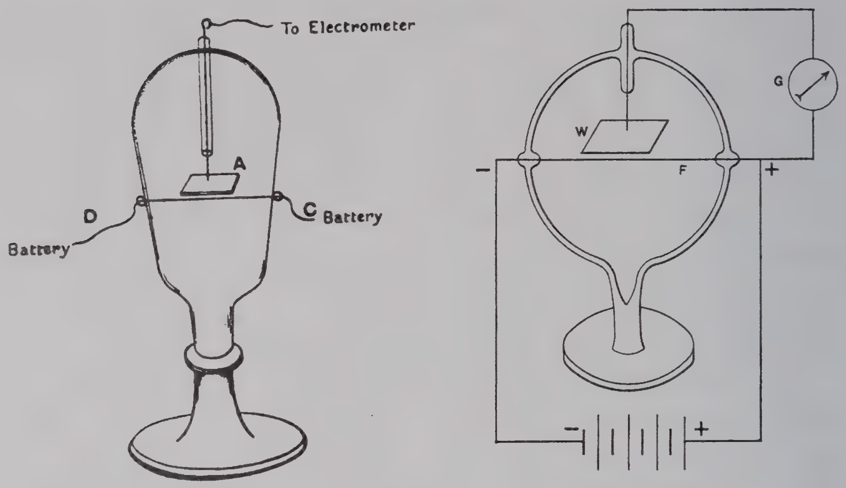
J. J. THOMSON DRAWING

ELSTER & GEITEL DRAWING

Fig. 22. J. J. Thomson reproduced an image of the Elster and Geitel configuration in his 1903 book (left) that was similar to the one that appeared in the original Elster and Geitel paper (right); however, Thomson deleted the wire MN from the Elster and Geitel configuration that appeared in their paper, which connected the center of the wire AB to the external binding post N. (Left: Thomson, *Conduction of Electricity*, 1903, p. 156; Right: Elster & Geitel, *Ann. d. Physik*, Vol. 31, 1887, Plate 1, Fig. 7)

Notably, Thomson's interpretation of the Elster and Geitel configuration without wire MN was much closer to De Forest's audion configuration than the actual Elster and Geitel configuration (see Fig. 23). This difference supports a contention that De Forest read Thomson's book rather than the original Elster and Geitel article, but it does not explain why De Forest made two other major alterations to the figure so that it matched his audion configuration. The most logical conclusion is that De Forest made those changes on purpose in an attempt to support a claim that he copied his audion configuration from Elster and Geitel's earlier disclosure in 1882, believing that it predated Edison's disclosure of the Edison effect configuration in 1883 and De Forest's disclosure of his valve configuration in 1904.

The error in the stated date of publication of the Elster and Geitel paper can also be explained by the presumption that De Forest discovered the Elster and Geitel configuration in Thomson's book but failed to check the actual reference in *Annalen der Physik*. It turns out that Thomson was the one who made the error in the date of Elster and Geitel's paper. Thomson added a footnote to the Elster and Geitel configuration with a reference containing the erroneous date. Thomson's footnote contained six entries



J. J. THOMSON DRAWING

De FOREST DRAWING

Fig. 23. De Forest's detector configuration shown on the left was almost identical to Thomson's incomplete version of the Elster and Geitel configuration on the right because both of these configurations were missing the wire MN that connected the plate circuit to the horizontal wire rather than to either battery terminal. (Left: AIEE lecture, 1906, p. 725; Right: Thomson 1903, p. 156)

on the subject of ionization produced by incandescent metals that were published by Elster and Geitel in *Annalen der Physik*, the first and incorrect entry being: "Elster and Geitel, *Wied. Ann.* xvi. p. 193, 1882." This is the same reference that appeared in De Forest's AIEE lecture. The correct reference to the Elster and Geitel paper with the experimental configuration in question was actually the fifth entry out of six to *Annalen der Physik* that appeared in the footnote of Thomson's book: "xxxi. P. 109, 1887."

Thomson also made the same error in a reference he made to the same Elster and Geitel article in his earlier book, *The Discharge of Electricity Through Gases*:

> "Elster and Geitel, *Wied Ann.*, 16, p. 193, 1882; 19, p. 588, 1883; 22, p. 123, 1884; 26, p. 1, 1885; 31, p. 109, 1887; 37, p. 815, 1889."[53]

De Forest was not the only one to be fooled by the two erroneous references to the Elster and Geitel experiment in Thomson's books. Owen Richardson, who developed the theory of thermionic emission from heated solids, cited the same Elster and Geitel paper using the same erroneous 1882 citation that appeared in Thomson's 1898 book. In a paper Richardson wrote as a graduate student in 1901, he began with the following sentence containing a reference to the Elster and Geitel paper at issue: "Ever since the original discovery by Messrs Elster and Geitel that the air in the neighborhood of a hot metal discharged electricity, several physicists have investigated the laws of this phenomenon."[54] The reference in this sentence was to this footnote that appeared at the bottom of page 286 in his paper: "Elster and Geitel, *Wied., Ann.* xvi. 1882, p. 193, and later papers."

De Forest Misrepresented the I-V Characteristic Curve of his Audion Bulb

De Forest presented an I-V characteristic curve that he claimed was measured for a double-wing audion of the type he presented in his AIEE lecture (see Fig. 24): "These curves were all taken with audions of the double-wing type."[55] The axes on his curve were reversed from the conventional way that scientific data was and still is presented. The independent variable (in this case, voltage) is normally displayed on the horizontal axis (abscissa), and the dependent variable (current) is normally displayed on

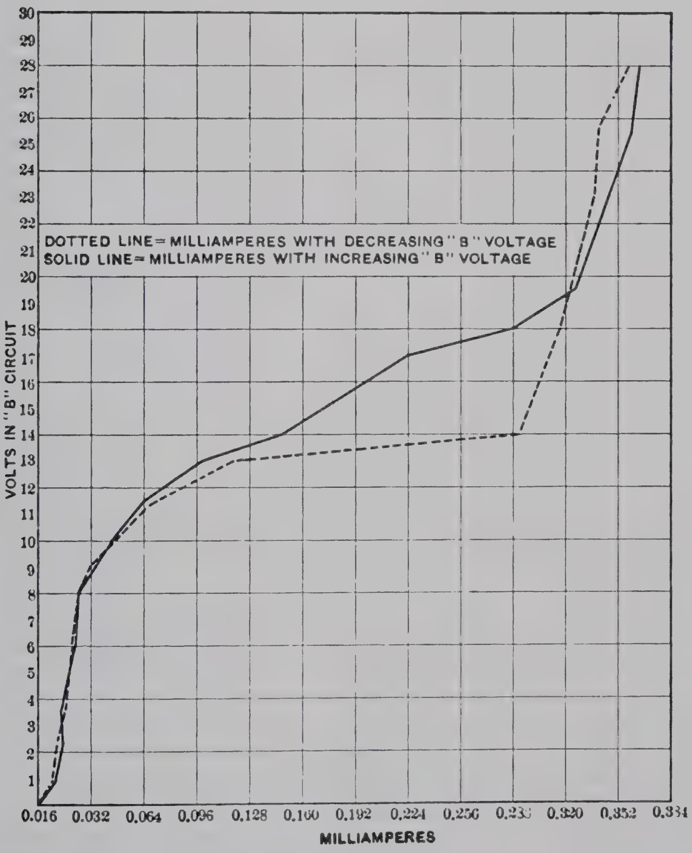


Fig. 24. De Forest claimed he measured this I-V characteristic curve for his double-wing bulb detector in which the voltage and current axes are reversed when compared to the accepted scientific convention where the x-axis represents voltage as the independent variable. (De Forest, AIEE lecture, 1906, p. 373)

the vertical axis (ordinate). De Forest reversed them for no apparent reason. He may have done so in an attempt to make his curve look different from Fleming's I-V characteristic curve for his valve that he published in March 1905. Regardless of why he reversed the axes, the conventional way to plot his data has been restored by rotating and flipping his curve (see Fig. 25).

It should be apparent to anyone familiar with the Edison effect that this I-V curve was not created by using data collected using the double-wing audion that he presented in his AIEE lecture with the plate circuit connected to the positive electrode of the filament battery (see Fig. 26). When the plate circuit lead is attached the positive terminal of the filament battery and the plate circuit voltage is set to zero, the resulting configuration is identical to Edison effect bulb where the galvanometer in the plate circuit registers a considerable current without a battery. Fleming developed a demonstration experiment to illustrate this effect for the Edison bulb (see Fig. 27).[56] When the switch on the left (connected to the negative pole of the filament battery) was closed, there was no flow of current in the galvanometer. However, when the switch on the right

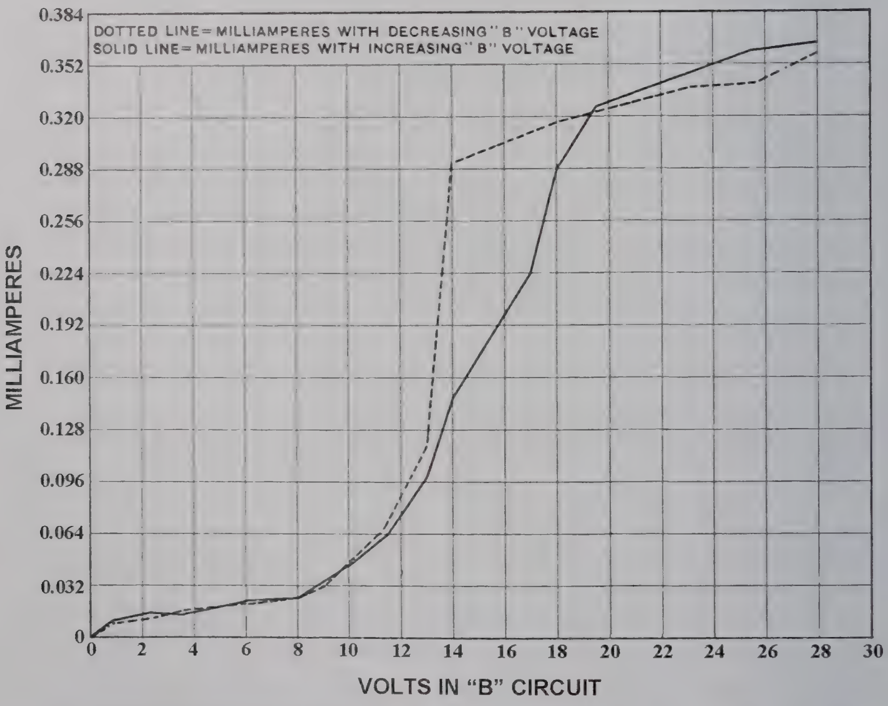


Fig. 25. The I-V characteristic of the previous figure is corrected by a 90-degree clockwise rotation and a 180-degree flip about the x-axis that places the voltage on the x-axis as the independent variable and the current on the y-axis as the dependent variable. (Author's curve correction)

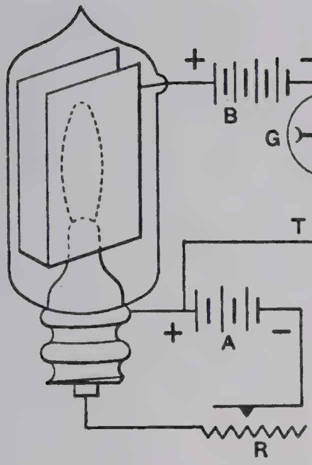


Fig. 26. De Forest connected the plate circuit of his double-wing audion to the positive terminal of the filament battery. (De Forest, AIEE lecture, 1906, p. 727)

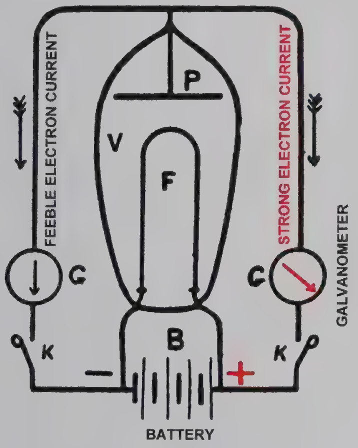


Fig. 27. Fleming developed this experiment to demonstrate that the Edison effect current in the plate circuit of an evacuated bulb is significant without a battery in the plate circuit when the galvanometer in the plate is connected to the *positive* terminal of the filament battery and it is essentially zero when the galvanometer is connected to the *negative* terminal of the filament battery. (Fleming, *Meetings of Royal Inst. of Great Brit.*, Vol. 23, June 1924, p. 162)

(connected to the positive terminal of the filament battery) was closed, there was a significant flow of current in the galvanometer.

De Forest's configuration should have exhibited a relatively strong current when the battery voltage in the plate circuit was zero, but the I-V characteristic curve shows the current in the plate circuit was zero when no voltage was applied. This is possible only when the battery in the plate circuit is connected to the negative pole of the filament battery. There is no error in the polarity of the filament battery in this figure because De Forest had confirmed that the plate circuit was connected to the positive pole of the filament battery in his patent application covering the double-wing audion:

> "Better results are obtained if the negative pole of the [plate circuit] battery B be connected to that end of the filament F to which the positive pole of the [filament] battery B' connected."[57]

This statement is proof that De Forest's I-V characteristic curve was not measured for the double-wing configuration, which had a plate circuit connection to the positive pole of the filament battery. From this statement is also apparent that De Forest tested his audion first with a plate circuit connection to the negative pole because he found that he got a better response when it was connected to the positive pole. This makes sense because De Forest's first patent application for an audion bulb was filed with the plate circuit connected to the negative terminal of the filament battery (see Fig. 28)—the same polarity that De Forest indicated in his patent application (see Fig. 29).

Note that De Forest used a different convention in marking the polarity of his batteries in his 1906 AIEE lecture than he did in either of his two-electrode audion patent applications. In his AIEE lecture, he designated the long lines of the two batteries in the double-wing audion circuit as the positive poles, while in his patent application for the same double-wing audion he designated the short lines as being the positive poles of the two batteries in the circuit. De Forest used the same battery convention in both of his audion patents, but he did not specifically mark the polarities of the batteries with plus and minus symbols in his first audion patent with a single plate, as he did with the double-wing audion. The reason for his change in battery polarity convention in his AIEE lectures from the convention he used in both of his audion patent applications is unknown.

Takeaway from De Forest's AIEE Lecture

The account De Forest gave in his October 1906 AIEE lecture was filled with erroneous statements and intentional deceptions. With one notable exception,

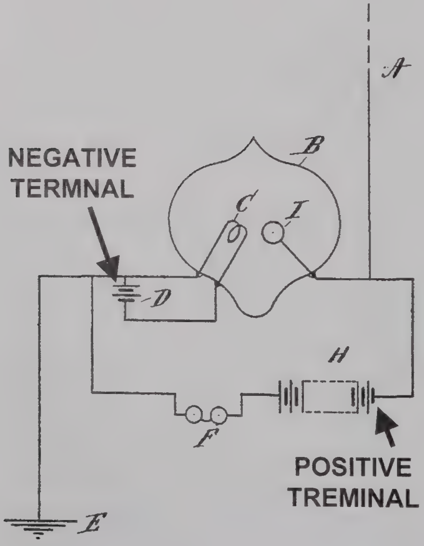


Fig. 28. The galvanometer in the plate circuit of the Fleming valve was connected to the negative terminal of his filament battery, as indicated in this figure from his U.S. patent application. (Fleming, U.S. Patent 803,684)

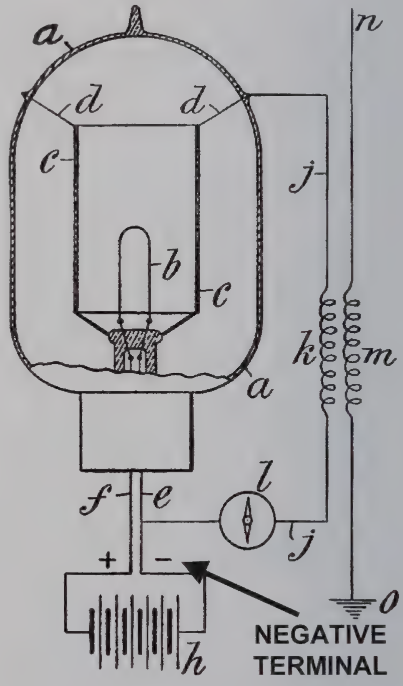


Fig. 29. De Forest's first patent application for an evacuated bulb audion shows the plate circuit connected to the negative terminal of the filament battery, which was indicated by a short line at the end of both batteries for the positive poles and a long line for the negative poles. (De Forest application for U.S. Patent 824,637, Fig. 3)

virtually all of the claims that he made during his AIEE lecture were abandoned in later accounts. The only claim he made for his two-electrode audion in this lecture that he maintained throughout his life was that his evacuated bulb audion acted as a relay or amplifier and therefore was much more sensitive than Fleming's valve. In the end, this claim also turned out to be false, although he never admitted it. The most significant false or deceptive claims that he soon abandoned were the following:

1. De Forest claimed that the genesis of his audion bulb was the Elster and Geitel configuration that appeared in a paper they published in 1882. This claim proved to be false because he misrepresented the configuration that appeared in their paper by altering it in three very significant ways so that it conformed to the audion configuration that he presented at the AIEE lecture. There can be no doubt that the Elster and Geitel configuration was not the genesis of his audion.
2. De Forest maintained for years that the Elster and Geitel paper was published in 1882, even after Fleming informed him more than once that their paper was published in 1887. Fleming was correct and De Forest was incorrect.
3. De Forest claimed that the flame detector he presented at his lecture was an "early state" of audion, but it was first documented in a patent application he filed on January 20, 1906—after he filed his first audion patent. He failed to mention that he had filed a patent application a year earlier, on February 2, 1905, for a much different flame detector of Hertzian radiation.
4. De Forest presented an I-V characteristic curve for his flame detector that turned out to be an I-V curve generated by Egon von Schweidler using an evacuated cavity with a surface exposed to the light from an arc lamp source to liberate electrons from the surface by the photoelectric effect.
5. De Forest presented an I-V characteristic curve that he claimed was measured using his double-wing audion with a plate circuit connection to the positive pole of the filament battery, but the curve was actually measured with the plate circuit connection to the negative pole of filament—just like the Fleming valve circuit.
6. De Forest erroneously claimed that Fleming connected the plate circuit of his audion to the positive terminal of the filament battery in the Elster and Geitel configuration appearing in an 1882 publication; Fleming actually attached his plate circuit to the negative terminal of the Edison effect tube circa 1887, about the same time the Elster and Geitel paper was published.

Judge Mayer's Opinion in Marconi vs. De Forest Trial (September 20, 1916)

Judge Julius Mayer was the judge who presided over the 1916 trial that resulted from the litigation between American Marconi and the De Forest Radio Telephone and Telegraph Company. He documented his decision on September 20, 1916, when he ruled that Fleming's two-electrode valve patent and De Forest's two- and three-electrode audion patents were valid and that Fleming's valve patent did not infringe any of De Forest's patents. He also found that De Forest's two- and three-electrode audion patents infringed Fleming's two-electrode valve patent.

Judge Meyer's ruling, published in the *Federal Reporter* in 1917,[58] revealed significant information on De Forest's testimony describing how he invented his two- and three-electrode audions. The focus of this section is on Judge Mayer's observations of De Forest's testimony and exhibits relating to his discovery and descriptions of his two-electrode audions. The actual trial testimony and exhibits will be recounted in Part II.

De Forest Changed his Story for the Genesis of his Audion

In his 1906 lecture, De Forest claimed the genesis of his two-electrode audion was the configuration in the Elster and Geitel paper. However, according to Judge Mayer's findings, De Forest claimed the genesis of both his two- and three-electrode audions was a flame detector configuration that he described in his U.S. Patent 979,276, which he filed on February 2, 1905 (see Fig. 5). Judge Mayer characterized this patent as his "parent patent," meaning that it was the genesis of his audions:

> "In endeavoring to resist plaintiff's attack, defendants have proceeded on the theory that, beginning with his parent patent, No. 979,275, antedating Fleming, De Forest gradually developed his first conception until finally it found practical exemplification in the two so-called three-electrode 'Audion' devices as to which plaintiff has confessed judgment. In line with this plan of defense, defendants have elaborately built up an unsteady theoretical structure, and upon this have superimposed an observatory from which they can see in the mind's eye only that which they call 'Audion' action."[59]

If his U.S. Patent 979,275 was his parent patent, then the asymmetric flame configuration he introduced in his AIEE lecture could not have been his early audion. Surely, De Forest chose his U.S. Patent 979,275 to be the parent of all his audions in this litigation because it was the only detector device with heated electrodes that he had documented before the priory date accorded to Fleming's valve patent application. De Forest would never have been accorded priority in a court of law for any kind of detector, flame or otherwise, that was not documented before the priority date of the Fleming valve. De Forest would continue to claim for the rest of his life that the genesis of his vacuum tube audion bulb was a flame configuration described in his U.S. Patent 979,275.

De Forest had Prior Knowledge of Fleming's Patent

Judge Mayer made the following statement in his written opinion, which he recalled from testimony given in the 1916 trial:

> "It must be remembered that De Forest in December, 1905, knew of Fleming's Royal Society paper of March, 1905, as appears from a reference to that effect in his application for a certain patent not here in issue (No. 823,402), where he used the expressions 'exhausted vessel' and 'heated to incandescence.'"[60]

The patent he referred to was entitled "Static Valve for Wireless Telegraphy," for which De Forest filed his application on December 9, 1905. Here is the paragraph cited by De Forest in this patent to which the judge referred:

> "The device V^{I}, [shown in Fig. 30] connected between the antenna at point b and earth, is an asymmetric resistance or electric valve which has been fully described by J. A. Fleming in a paper published in the *Proceedings of the Royal Society of London*, March 16, 1905, to which reference may be had for a more complete description thereof than need to be set forth herein. Suffice it to say that the exhausted glass vessel Q" contains the filament F' heated to incandescence by the battery B' and a metal cylinder D', which surrounds the filament F'. This type of valve passes positive electricity from the cold terminal D' to the heated terminal F' more readily than in the opposite direction."[61]

The device "V^{I}" shown in "Fig. 1" of this patent was a Fleming valve that is reproduced here as Fig. 30. De Forest referenced an article by Fleming that appeared in the *Proceedings of the Royal Society of London*,[62] which contained a complete description of Fleming's valve. It included a schematic diagram of the Fleming valve that actually appeared in Fleming's valve patent (see Fig. 29); it showed how the valve was connected to an antenna and ground to function as a detector for radiotelegraphy. The article also included a set of I-V characteristics for three different filament voltages (see Fig. 31). The article even revealed three possible plate configurations, one of which was a two-plate configuration (see Fig. 32 c), which appeared in the audion in De Forest's 1906 AIEE lecture.

Fleming also revealed the following information in the paper cited by De Forest that provided all the information that De Forest needed to engage a glass blower to fabricate a sensitive, functioning detector:

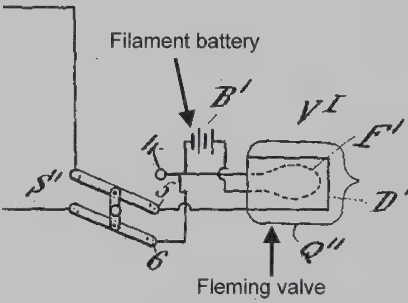


Fig. 30. De Forest filed an unrelated patent on Dec. 9, 1905, complete with this image of Fleming's valve; this patent application also revealed that De Forest had read an article by Fleming that appeared in the *Proceedings of the Royal Society of London*, which included a schematic diagram of the valve he used in his patent application accompanied by a detailed description of its technical parameters. (De Forest U.S. Patent 823,402)

1. The curves in Fig. 31 indicated that the vacuous space would possess a maximum conductivity when a potential difference of about 20 volts was applied to the electrodes.
2. The bulb should be highly exhausted

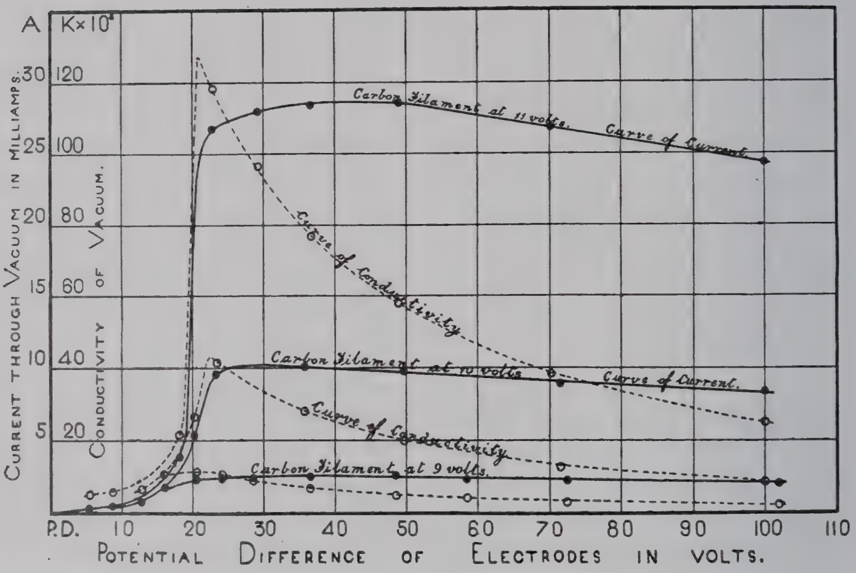


Fig. 31. De Forest admitted that he had read an article by Fleming that appeared in the March 1905 issue of the *Proceedings of the Royal Society of London* featuring three I-V characteristics for his valve detector, one for each of three slightly different filament voltages. (Fleming, *Proc. of the Royal Society of London*, Vol. 74, Mar. 1905, p. 483)

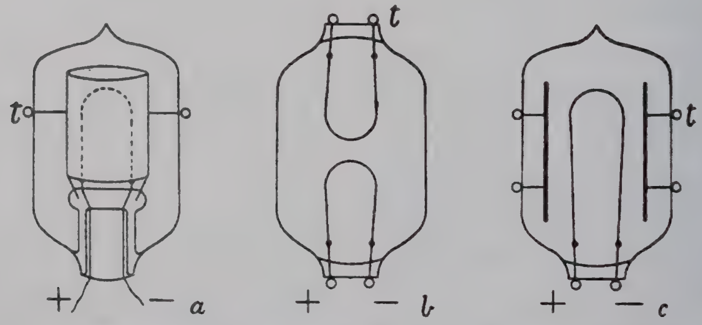


Fig. 32. Fleming disclosed three possible plate configurations for his Fleming two-electrode valve detector in his article in his March 1905 publication: (a) a cylinder surrounding a filament, (b) two opposing electrodes consisting of filaments that could be heated with an external battery, and (c) two opposing plates on opposite sides of a filament with external leads that could connect the plates together or allow them to be used separately as a three-electrode device. (Fleming, *Proc. of the Royal Society of London*, Vol. 74, Mar. 1905, p. 478)

to the pressure normally used in an incandescent light bulb with a carbon filament, and the metal cylinder or plate should be free from occluded air.

3. One carbon filament should be used, and a platinum wire should be sealed into the bulb terminating in a plate or cylinder of platinum, aluminum, or other metal surrounding the filament.
4. The cylinder should be cool and the carbon filament should be at a temperature not much above the melting point of platinum (1768 °C).
5. The primary coil of this oscillation transformer should have one terminal connected to the earth and the other to a long insulated rod that acts as an aerial or electric wave collector. To prevent the direct action of the transmitter upon the secondary coil by simple electromagnetic induction, it would be best to wind the secondary coil in two equal parts in opposite directions and to wind the primary in a corresponding manner.

Recall that De Forest was well aware of Fleming's valve before he signed his first audion patent application for U.S. Patent 824,637 on January 13, 1906. He documented the fact that he had read Fleming's March 1906 publication describing Fleming's valve detector in some detail in an unrelated patent application describing a static valve eliminator (U.S. Patent 823,402), which De Forest signed on December 6, 1905. However, there was no evidence that De Forest knew Fleming had filed a U.S. patent for his valve because Fleming's U.S. valve patent was not issued or published until November 7, 1905.

Judge Mayer reported one more important fact, namely that De Forest had sent a letter to his patent attorney dated December 21, 1905, that revealed De Forest was aware of Fleming's patent before he signed the patent application for his first vacuum tube audion:

> "It must be remembered that De Forest in December, 1905, knew of Fleming's Royal Society paper of March, 1905.... Further, on December 21, 1905, he instructed his solicitor to 'look out for Fleming's recent patent.'"[63]

In the last line of this citation, Judge Mayer revealed that De Forest was aware of Fleming's patent before he signed his vacuum bulb audion patent application, but he did not reveal certain contents of this letter that would prove De Forest had read Fleming's entire patent before he prepared a draft of the patent application that he sent to his attorney. In Part II of this paper, the contents of this letter and the facts surrounding its preparation will be revealed. This letter is the smoking gun that proved De Forest copied Fleming's patent.

De Forest's Audion as an Amplifier/Relay was not Novel

Recall that De Forest had admitted his audion bulb was identical to the Fleming valve, but he claimed that the battery he used distinguished his audion from the Fleming valve. He asserted the battery provided the energy to amplify the signal, thus making his audion much more sensitive and suitable for radiotelegraphic applications, whereas the Fleming valve without a battery was insensitive and useful only for measurement in the laboratory. Judge Mayer claimed this issue was one of the most contested points in controversy during the trial:

> "Fleming's theory, as has already been stated, was that of rectification; while defendants account for the action of their 'Audion' on the theory that it is a telephone relay, or, in other words, that its products are alternating currents of 'audio' frequency and of the local energy, and not of the 'input' energy. As a result of these differences, the effect and relation of the local battery was one of the sharply contested points in controversy."[64]

Judge Mayer concluded that a battery had been used in virtually all previous wireless detector circuits and there was no novelty for the battery in De Forest's detector circuit. He also pointed out that Marconi had documented the use of a battery in his coherer circuit with earphones and he was entitled to use the same circuit he had used before with the new device he had invented. Perhaps the best example of Marconi using a battery in a detector was the one he described in his patent application filed in 1901 (see Fig. 33).[65] Judge Mayer made this finding:

> "The local battery is used to bring the lamp detector to the sensitive point of its characteristic curve, and the potentiometer is the simple and effective

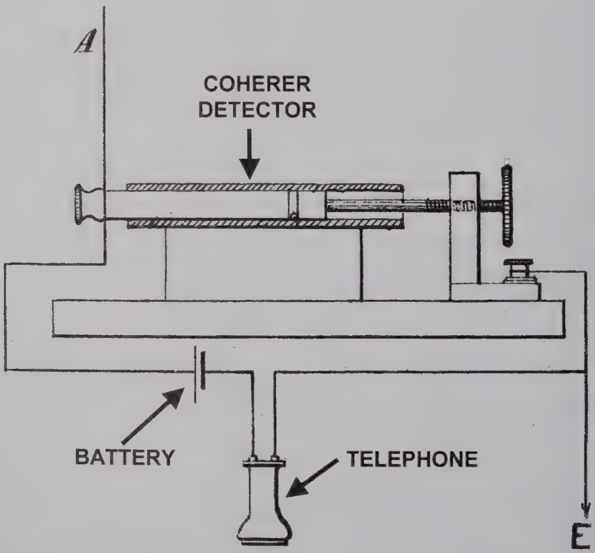


Fig. 33. Perhaps the best example of Marconi using a battery and telephone receiver in a wireless detector circuit was the one he used with the Italian Navy coherer, which was documented in a patent application he filed on Sept. 10, 1901. (G. Marconi, UK Patent 18,105)

device which, varying the local battery, accomplishes this task. Nearly all prior art detectors were used in this way—the coherer of Marconi and Lodge; the microphone of Hughes and Branly; the electrolytic of Fessenden, Vreeland, and others; and the crystal of Bose. Plaintiff's Exhibits 77 and 82.

"The use of the local battery to locate the sensitive point on the characteristic curve was well known and accepted as of Fleming's time, and, as appears by his 1905 lecture, was fully understood by him. See, also, particularly, Vreeland patent, No. 780,842, Plaintiff's Exhibit 82. Plaintiff is undoubtedly entitled to use the Fleming detector with a well-known instrumentality, and therefore to employ the variable local battery, for practically all the prior art detectors required local batteries to locate the operating points. Plaintiff is likewise entitled to use the Fleming device in the ordinary detector circuits of the prior art. The circuits of the Marconi patent, No. 627,650, are the specific circuits which plaintiff has used, and the modern operative Fleming device has simply been substituted for the coherer in old and familiar circuits (Q. 145, 146, et seq.)."[66]

De Forest Infringed Claims 1 and 37 of Fleming's Patent

Judge Mayer ruled that De Forest's two-electrode audion bulb, described by the claims in his U.S. Patent 824,637 and divisional U.S. Patent 836,070, infringed Claims 1 and 37 of Fleming's U.S. Patent 803,684. (The U.S. Patent Office required De Forest to file the divisional patent because an examiner ruled that the one device with a single heated electrode in the original patent application was a different invention from the other five configurations in that patent.) The divisional patent used essentially the same configuration and language that appeared in the original patent. The bulb configurations in both De Forest patents were identical and they were also the same as the configuration in Fleming's valve patent (see Fig. 29), with the only difference being the shape of the single cold plate.

That the claims in De Forest's divisional patent were virtually identical to the claims in Fleming's patent is obvious by comparing independent claims in both patents (see Table 5). The Fleming patent had two independent claims (1 and 37), while the De Forest patent had one. The first claim of a patent, generally known as the independent claim, is a stand-alone claim that contains all the limitations necessary to define an invention.[67] The claims following the independent claim are dependent claims that refer to the independent claim and must further limit the independent claim. By law, each claim must be a single sentence that starts with a capital letter and ends with a period. Multiple limitations that appear in each claim must be separated by commas. Most often there is only one independent claim per patent, but in the case of Fleming's patent, Claim 37 was a second independent claim. Claim 1 defined Fleming's valve invention, Claims 2–36 were dependent claims to

Table 5. Comparison of the single independent claim that appeared in De Forest's divisional U.S. audion patent (U.S. Patent 836,070) with the two independent claims that appeared in Fleming's U.S. valve patent (U.S. Patent 803,684).

Fleming Valve Patent 803,684 Claims 1 and 37	De Forest Audion Patent 836,070 Claim 1
What I claim is—1. The combination of a vacuous vessel,	I claim—1. An oscillation-responsive device comprising a partially-exhausted receptacle,
two conductors adjacent to but not touching each other in the vessel,	two separated electrodes sealed in said receptacle,
means for heating one of the conductors,	means for heating one only of said electrodes,
and a circuit outside the vessel connecting the two conductors.	a local circuit including a source of electrical energy and a signal-indicating device electrically connected with said electrodes,
37. At a receiving-station in a system of wireless telegraphy employing electrical oscillations of high frequency a detector comprising a... means for detecting a continuous current in the circuit, and means for impressing upon the circuit the received oscillations.	means whereby electrical oscillations may be impressed upon the gaseous medium intervening between said electrodes,*

* This phrase in De Forest's first independent Claim 1 is realigned with the very similar words in Claim 37 in Fleming's patent. The missing words represented by the dots in Claim 37 are not repeated because they are identical to the same words that appear verbatim in Claim 1.

further limit Claim 1, and Claim 37 was a single independent claim that specified the invention was to be used in the receiving station in a system of wireless telegraphy.

A description of how the two devices worked appeared in the descriptive portion of their respective patents that constitute the main body of the patent known as the "Specification." Fleming claimed his valve detector was based on the nonlinear principle of rectification that converted high-frequency currents to low-frequency currents that could be detected by a galvanometer or any other suitable detection device used in radiotelegraphy. He also claimed that a very high vacuum was most desirable. De Forest's patent claimed: "Electromagnetic signal waves may be impressed upon said gaseous conducting medium to alter its conductivity, and a signal indicating device operatively connected with said gaseous conducting medium, whereby alterations in the conductivity of the latter may be made manifest."

De Forest's device depended on the conductivity of a gaseous medium in the bulb and a source of heat to ionize the gas that produced the conductivity.

Fleming's device did not require any gas in the bulb, conducting or otherwise, but it did depend on having a highly incandescent filament to emit copious amounts of electrons that produced a current across the electrodes when the applied potential on the cold electrode was positive. Note that an inventor does not have to know how a device works to be awarded a patent, but it does have to work. Conversely, an inventor cannot escape patent infringement by simply claiming that the same device operates by a different principle.

Judge Mayer Declared De Forest's Double-wing Audion to be Worthless

In De Forest's AIEE lecture, he described a double-wing audion bulb that had a different configuration and function than the one covered by his original patent. Here is how he described the function of this version of his audion in his lecture:

> "The Audion, to a greater extent than any other responder, is self-tuned. I mean that by regulating the heating current, the potential between wing and filament, or the distance between these, the Audion can be made to a great extent selective *per se* to certain received impulses. And the determining factor here is not merely the frequency of the electrical oscillation; the spark frequency, or factors determining the total amount of energy received during a very brief unit of time, determine to an extent the amount of its response. Thus with 12 volts across it, it may give a loud response to a transmitter A; and with 10 volts 'bring in' another transmitter B to the almost complete exclusion of A, although A and B are of equal power and of approximately the same wave-length, but differing considerably in spark frequency."[68]

This device was covered by a second patent filed in August 1906, which described an audion that he claimed was self-tuning without the need for a separate tuning circuit that was required in all other wireless systems of the day. This tuning was supposed to be achieved in part by altering the distance between the hinged double-wing plates with a magnet (see Fig. 34):

> "A convenient means of varying the distance between the electrodes F' F' is to hinge the wing which constitute the electrode F to the base 2 by the hinges 1 1.... When the audion is to be attuned to oscillations of a given frequency by varying the separation of the electrodes, the adjustment produced by the magnets 6 6 must be empirically determined."[69]

De Forest was asked to demonstrate the self-tuning feature of this audion at the trial, which was given the name "selective per se audion," but he was unable to do it. Julius Mayer took note of this demonstration because he wrote this statement in his opinion: "The so-called selective per se patent, No. 841,386, is so utterly useless that it might well be declared invalid." While he did not invalidate De Forest's audion patent, the appellate court later agreed with Judge

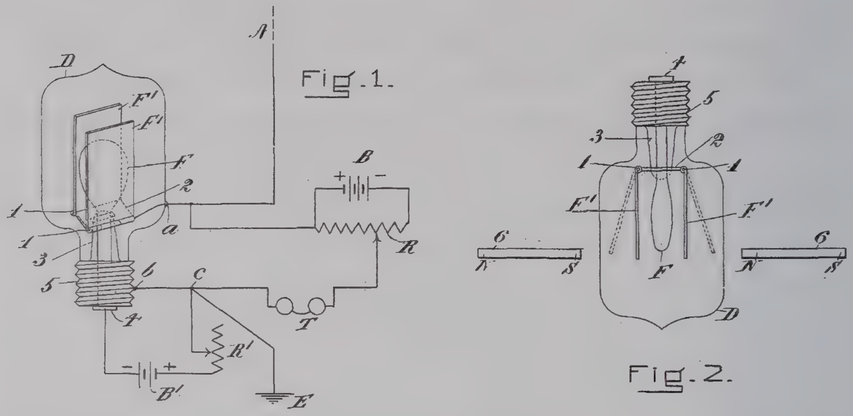


Fig. 34. De Forest claimed his double-wing audion was self-tuning so there was no need for a separate tuning circuit that was required in other wireless systems of the day. This tuning was supposed to be achieved in part by altering the distance between the hinged double-wing plates with a magnet. (De Forest U.S. Patent 841,386, filed Aug. 27, 1906)

Mayer because appellate Judge Charles Hough did invalidate this patent during the appeal that De Forest filed after losing the suit in Judge Mayer's district court:

> "The seventh counterclaim patent (841,386) is proved to be inoperative. The patentee declares that by 'suitably varying the length of interelectrode medium' he can make the audion 'per se selectively responsive.' Assuming this last phrase to mean 'make it work,' defendant at the trial did not do it, and we think refused to try. It follows from the foregoing that we hold patent No. 841,386 void."[70]

It is difficult to understand why De Forest would choose this second and unusual form of audion to introduce his audion invention at his AIEE lecture rather than the basic audion form described in his first audion patent application. Perhaps he wanted to present an invention that was different in function from what Fleming had described in his patent.

Takeaway from Judge Julius Mayer's Opinion

1. **De Forest Revised the Genesis of his Audion:** The most important conclusion that can be drawn from Judge Mayer's opinion is that De Forest abandoned the assertion he made in his AIEE lecture that the genesis of his evacuated bulb audion was the Elster and Geitel paper. Presumably, he made this decision because he could not prove in court that he documented his evacuated bulb detector configuration before the priority date of Fleming's valve patent. The only relevant document De Forest had prepared before the priority date of

Fleming's valve was his flame detector patent that he filed on February 2, 1905. De Forest was able to prove in the trial that he signed the application on November 4, 1904, which preceded the priority date of Fleming's patent. By U.S. patent law, the priority date of Fleming's U.S. patent was set at the filing date of his UK Patent 24,850, which was November 16, 1904. Since De Forest's earliest flame detector patent had a priority date that preceded the priority date of Fleming's patent by eight days, De Forest developed a new strategy by arguing the flame detector he described in the patent application filed in 1905 was the genesis of his evacuated bulb audion.

2. **De Forest Admitted Prior Knowledge of the Fleming Valve:** Another important conclusion from Judge Mayer's opinion was that De Forest was aware of the Fleming valve and virtually of all technical details required to define or fabricate a Fleming valve almost a year before De Forest filed his first audion patent application. In an unrelated patented application, De Forest had revealed that he knew all about the Fleming valve detector and even cited the paper that Fleming had published in March 1905 that described all of the details of his valve patent and revealed that it could be used as a detector of Hertzian radiation in wireless telegraphy.
3. **De Forest Could Not Differentiate his Audion by Citing his External Circuit:** In 1906, De Forest had claimed in his 1906 lecture that his audion bulb was identical to Fleming's valve but that his audion invention was distinguished from Fleming's valve because he used a battery in the plate circuit whereas Fleming did not. Whether or not the vacuum tube worked differently with or without a battery was hotly debated in the trial but in the end, Judge Mayer ruled that Fleming had the legal right to use a battery in his external circuit even though he did not specify its use in his patent. Judge Mayer pointed out that a battery appeared in virtually every radio detector that had preceded the Fleming valve patent—including and in particular a coherer circuit that Marconi had used with both a battery and telephone. In the end, Judge Mayer ruled that the presence of an external battery in De Forest's circuit could not be used as a factor in differentiating De Forest's audion bulb invention from Fleming's valve bulb invention.

De Forest's Account in his Franklin Institute Lecture (February 1920)

De Forest's lecture that he gave at the Franklin Institute in 1920 was the second and last major lecture in which De Forest described in some detail how he invented his two-electrode audion. His other detailed audion lectures focused mainly on his three-electrode audions, which are not at issue here. The account in this lecture did not materially change in the thirty years between the Franklin lecture and his autobiography. The detailed account that appeared in his 1950 autobiography was taken almost verbatim from the 1920 lecture. The account in the Franklin Institute lecture was very different from the version he gave at the AIEE lecture.

De Forest began the lecture at the Franklin Institute with the same story about his observation of the Welsbach lamp in 1900 but provided a different account of the configuration he used to discover the flame detector:

> "The first 'commercial' audion, as it originally appeared in 1906, was therefore no accident, or sudden inspiration. For failing to find in an incandescent mantle the genuine effect or response to electrical vibrations I next explored the Bunsen burner flame, using two platinum electrodes held close together in the flame with an outside circuit containing a battery of some 18 volts and a telephone receiver."

This description conflicts with the version that De Forest gave at his 1906 AIEE lecture where he stated he first found the response in an incandescent mantle: "By soaking the mantle in a potassium or sodium solution and drying, I was finally able to pass a small current from a dozen dry cells through the flame surrounding it, using two platinum electrodes with a telephone receiver in circuit, and get a faint response to the genuine Hertzian wave."

The remainder of De Forest's account was concise, if not accurate, but lacked any documentation to support it. De Forest described three different phases of audion development accompanied by three different configurations, the first dating to 1903, the second dating to 1904, and the third dating to 1905. Since the three configurations were dated by year but not by month, it is impossible to accurately date the accomplishments. The time that passed between any two of his developments could have been as short as one month or as long as two years. It will become evident in Part II that his entire account was highly inaccurate.

Worse yet, the developments of the two-electrode audion cannot be correlated to the dates of the three detector technologies that he used in De Forest Company systems between 1901 and 1906. The adage "necessity is the mother of invention" was particularly applicable to De Forest. The only time De Forest was interested in developing a new detector technology was when an existing technology was failing and needed to be replaced. The electrolytic receiver he appropriated from Fessenden in late 1903 was spectacularly successful for almost two years between December 1903 and October 1905, and there is no indication in the literature that he was interested in any other detector technology during this period. It was not until October 16, 1905, when the De Forest Company was found guilty of infringing the Fessenden patent and was subsequently proscribed from using the electrolytic detector that De Forest became interested in finding a new non-infringing detector technology.

The account in De Forest's autobiography in 1950 was virtually identical to the account in the *Journal of the Franklin Institute* in 1920, although the paragraphs do not follow in quite the same order. Also, the paragraphs describing the characteristic I-V curve of his audion detector in his Franklin Institute lecture did not appear in his 1950 autobiography. The following three titled paragraphs constitute a synopsis of the lecture taken from the published account.

Phase 1: De Forest's Flame Detector (1903)

De Forest claimed that after he failed to find the desired response of Hertzian waves in the incandescent mantle of a Welsbach lamp, he then explored the use of a Bunsen burner flame for that purpose. Referring to the flame detector configuration of Fig. 35, he claimed that in 1903 he "clearly heard in the telephone receiver the signals from a distant wireless telegraph transmitter." In the text of his autobiography, he expanded on this claim by stating that he heard signals from ships transmitting Hertzian waves from the New York harbor, which was located at a distance of about one mile from his laboratory. Since the wireless signals he received at a distance of one mile were orders of magnitude higher than those received at practical distances of interest at that time, say 50 to 100 miles, the reception of these "clear signals" does not support his later contention that this flame detector was quite sensitive.

De Forest's patent application for his flame detector, U.S. Patent 979,275, which was accorded a priority date of November 4, 1904, supported his contention that he developed a flame detector, but the late priority date neither supported nor conflicted with his contention that he discovered this detector as early as 1903. Having said that, an unpublished document was submitted into evidence at the 1916 trial that provided irrefutable evidence De Forest had documented this form of flame detector configuration even before 1903. The circumstance of this unpublished document will be presented in Part II.

FIG. 1.

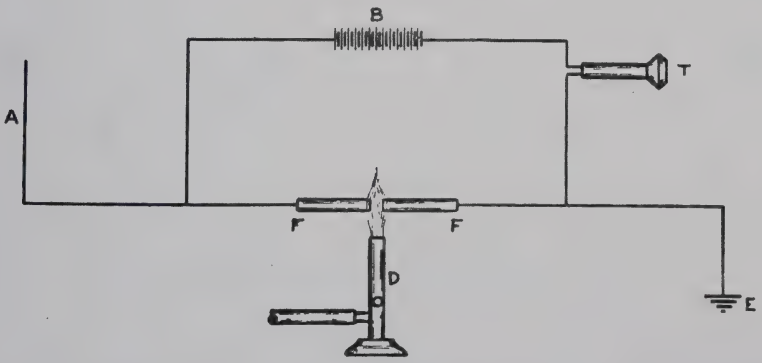


Fig. 35. Using the flame detector configuration pictured here, De Forest claimed in his Franklin Institute lecture that in 1903 he had "clearly heard the signals from a distant wireless telegraph transmitter in a telephone receiver." (*J. Franklin Inst.*, Vol. 190, 1920, p. 3, Fig. 1)

Phase 2: De Forest's Transition to a Vacuum Bulb (1904)

Referring to the configuration reproduced from his Franklin Institution lecture in Fig. 36, De Forest claimed that introduced a plan in 1904 for an early carbon filament detector in an evacuated bulb:

> "At the period now under consideration, 1903–1905, I was familiar with the Edison effect and with many of the investigations thereof carried on by scientists, Prof. Fleming among others. In 1904 I had outlined a plan of using a gas heated by an incandescent carbon filament in a partially exhausted gas vessel as a wireless detector, in place of the open flame. But here the rectification effect between hot filament and a cold electrode was not considered. Two filaments, heated from separate batteries would give the desired effect equally well."[71]

The key word in his account was the word "plan." He did not say that he documented, fabricated, or tested an evacuated bulb with two separate filaments, heated or otherwise. In fact, De Forest admitted that he could not fabricate evacuated bulbs at this time. It turns out that De Forest was unable to identify a document or even a single person to whom he had disclosed such a plan in 1904. How could De Forest possibly know in 1904 that "two filaments, heated from separate batteries would give the desired effect equally well"?

According to the sworn testimony from De Forest and his patent attorney, George K. Woodworth, De Forest disclosed this "plan" for the first time to his patent attorney at a meeting on November 24, 1905. Woodworth documented this disclosure with a handwritten note with a sketch that he initialed and stamped with the date of the meeting (see Fig. 37). Note that the notation on

FIG. 2.

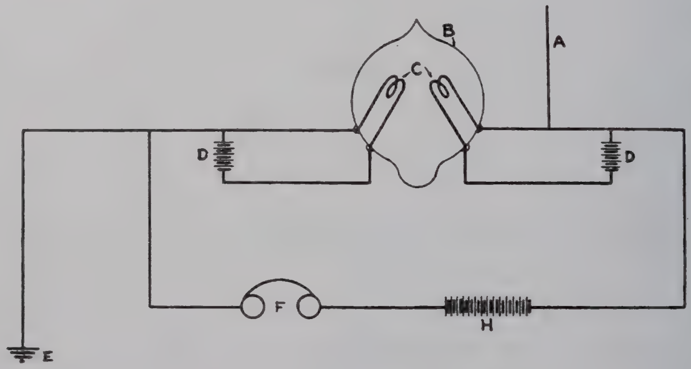


Fig. 36. De Forest referred to this figure in his Franklin Institute lecture when he claimed that in 1904 he had "outlined a plan of using a gas heated by an incandescent carbon filament in a partially exhausted vessel as a wireless detector in place of the open flame." (*J. Franklin Inst.*, Vol. 190, 1920, p. 4, Fig. 2)

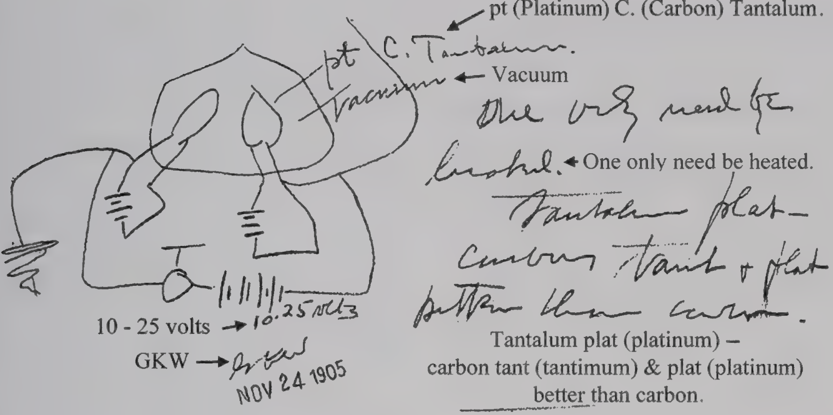


Fig. 37. According to sworn testimony in the 1916 trial, De Forest disclosed this plan for the first time to his patent attorney, George K. Woodworth, at a meeting on November 24, 1905; the plan was documented with this sketch drawn by his patent attorney. (Preview of unpublished 1916 trial exhibit documented in Part II)

the sketch stated: "only one [filament] need be heated." The complete document and the circumstances surrounding the disclosure of this document will be presented in Part II.

The same configuration that De Forest revealed to Woodworth in the November meeting was documented and described in detail by Fleming in a paper that was published seven months before in the April 1905 issue of *Technics* (see Fig. 38).[72] Referring to this figure from his article, Fleming wrote: "A bulb containing two carbon filaments forming the two electrodes, one of which can be rendered incandescent, will act as a vacuum valve." Fleming's observation presages the same sentiment that Woodworth noted on his sketch seven months later: "Only one need be heated." It is likely that De Forest read this paper because he admitted in his Franklin Institute lecture that he was familiar with many of Fleming's investigations published during his period.[73]

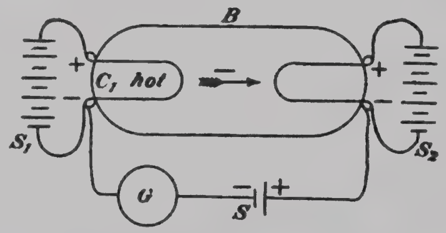


FIG. 2.

B.—Vacuum bulb.
C_1.—Carbon filament to be rendered incandescent by insulated battery S_1.
G.—Galvanometer.
S.—A single cell sending negative electricity from hot filament to the cold one.

Fig. 38. The same configuration that De Forest revealed to Woodworth in their November meeting was documented and described in detail by Fleming in a paper that was published seven months before in the April 1905 issue of *Technics*. (Fleming, *Technics*, Vol. 3, Apr. 1905, p. 317)

Phase 3: De Forest's First Audion Bulb Configuration (1905)

Referring to Fig. 39 reproduced from his lecture at the Franklin Institute, De Forest introduced his first two-electrode audion in 1905 with the following words:

> "The ordinary small incandescent lamp of that epoch supplied admirably the conditions I required, merely by the introduction of a second electrode. That added electrode could be either hot or cold. Obviously therefore, use it cold, avoiding thus the unnecessary battery. Then obviously, too, I must so connect my telephone "B" battery as to make this cold electrode positive, for otherwise no local current could flow through the gaseous space in the lamp between the unlike electrodes."

Before analyzing De Forest's account associated with the configuration in this figure, it is important to note that the configuration in this figure is not the same as the configuration that appeared in his first audion patent application for U.S. Patent 844,637, which was reproduced here as Fig. 28. The configuration in this figure, which he has dated to 1905, shows the plate circuit is connected to the positive pole of the filament battery. However, the plate circuit was connected to the negative pole of the filament battery in his first audion patent filed on January 18, 1906. It was not until August 1906 that De Forest filed his second audion patent application, the first one to show the connection to the positive pole of the filament battery. It will be clearly shown in part II that the polarity of the connection to the filament battery was fundamental to the demonstration test that De Forest devised, which enabled him to give the false impression that the Fleming valve was insensitive. Also, note that De Forest is once again not using the accepted convention that the long plate of the battery in a schematic diagram represents the positive pole of the battery.

There is little doubt that De Forest introduced his first two-electrode audion bulb in the latter part of 1905, but the real question is whether he introduced

FIG. 3.

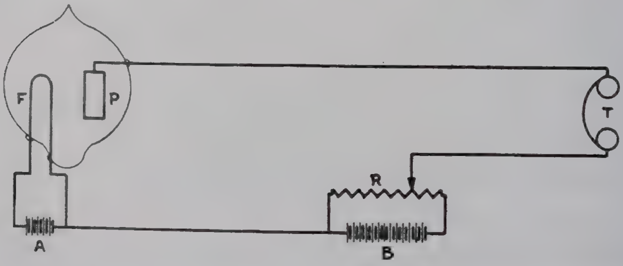


Fig. 39. De Forest claimed that in 1905 he found the ordinary small incandescent lamp of that epoch would be a suitable detector by introducing a second electrode and adding a "B" battery and telephone receiver into the circuit. (*J. Franklin Inst.*, Vol. 190, 1920, p. 5, Fig. 3)

his audion bulb before or after he read the papers that Fleming published earlier in 1905 where he described his valve detector in detail. For example, De Forest admitted reading the article he published in the March 1905 issue of the *Proceedings of the Royal Society of London*, but he never admitted exactly when he read it. This article contained the same evacuated bulb configuration that appeared in Fleming's patent (see Fig. 29), and the text contained all the detail that De Forest needed to describe the same audion configuration that Fleming had published. Fleming also provided the I-V characteristic curves in this publication that were almost identical to the I-V curve that De Forest produced in his 1906 AIEE lecture.

Judge Mayer revealed that De Forest had requested the firm of H. W. McCandless & Company to fabricate the evacuated bulbs for the first time in December 1905: "That these patents dealt only with the heated gas idea is clear from De Forest's correspondence with his solicitor in December, 1905 and January, 1906, from his ordering incandescent lamps from one McCandless in the same December and January." Gerald Tyne, who was originally in possession of the 1916 trial documents, was kind enough to provide George H. Clark in 1944 with McCandless Company records, many of which had been produced at the trial. A McCandless record sheet documented these two orders as being on December 4, 1905, and January 5, 1906. McCandless testified that these were the first two orders to be placed by the De Forest Company. This McCandless record sheet was published by the Tube Collectors Association in 2003.[74]

While this record supports the claim that De Forest had documented his audion bulb in 1905, it does not prove whether he documented it before or after reading Fleming's paper published in March 1905. De Forest never did provide any documentation or other evidence to prove that he created this bulb configuration before the date he documented the configuration for his patent attorney.

De Forest's I-V Characteristic Curve

After presenting an account of how he developed his two-electrode audions, De Forest presented a sketch of what he claimed was representative of a typical I-V characteristic curve for his early audions. He once again mislabeled the two axes in this figure, an error that is corrected here by interchanging the labels "current" and "voltage" on the two axes. This change also required changes to the spacing of the lines that he had placed at the upper knee of the curve (see Fig. 40). A few additional words have also been added to his original drawing to clarify De Forest's explanation of how the audion worked. These alterations to his original figure are highlighted in red.

De Forest claimed that he could adjust the "B" battery so the audion could operate at either knee of the curve, both of which are readily apparent in the figure. De Forest chose the upper knee to describe how his audion operated:

> "If now the "B" battery potential [i.e., battery voltage] was so adjusted that the detector was operating on

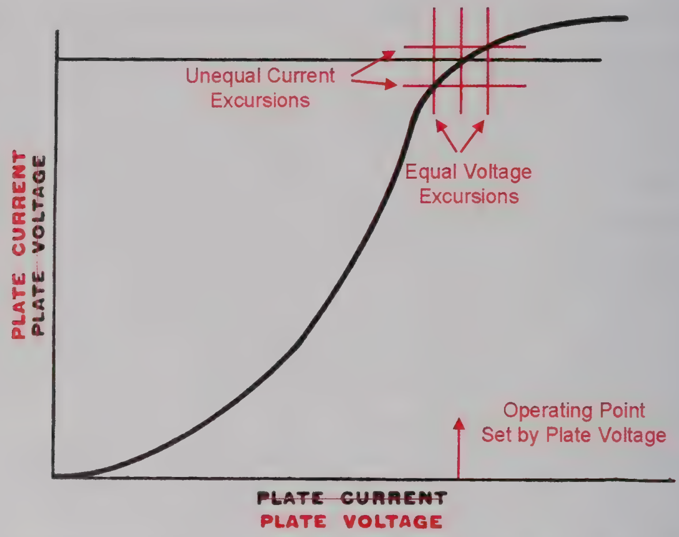


Fig. 40. In his Franklin Institute lecture, De Forest presented a drawing of what he claimed was the general form of an I-V characteristic curve for an early audion that he employed; an error in his sketch has been corrected in red by interchanging "plate voltage" and "plate current" labels on the two axes. (*J. Franklin Inst.*, Vol. 190, 1920, p. 5, Fig. 4)

> either knee of this curve the increase to this locally applied voltage, resulting from the positive halves of the wave-train, would produce a greater (or less) increase in the local current flowing across the gap than would the negative halves of the wave-train produce a decrease (or increase, as the case might be). In other words, the responsive action of this two-electrode audion was due to the asymmetry of its characteristic curve, rather than its rectifying property. The latter property [i.e., rectification] could be made to aid, to increase the intensity of the signal produced originally and mainly by the so-called 'trigger,' or genuine *relay* action of the device, which was always *controlling* and local energy by means of a much smaller incoming energy." [italics and parentheses by De Forest]

In plain English, he meant that when the excursions of voltage (caused by Hertzian oscillations) about the operating point were equal, the resulting excursions in currents were unequal, which over many oscillations resulted in a net DC current component that could be detected with a galvanometer or telephone receiver. This is the process Fleming defined as rectification, but De Forest rejected that view by stating: "In other words, the responsive action of this two-electrode audion was due to the asymmetry of its characteristic curve, rather than its rectifying property."

This is an astonishing statement for De Forest to make in 1920 when most knowledgeable scientists and radio engineers knew that the two-electrode thermionic tube operated by the principle of rectification, which was first revealed by Fleming in early 1905. De Forest's unfathomable description had been soundly rejected by then: "The so-called trigger, or genuine relay action of the device, which was always controlling the local energy by means of a much smaller incoming energy." What is a "so-called trigger" or "genuine relay action," and how could De Forest determine that the "trigger action" contributed much more to the detection of Hertzian waves than the "rectification property." De Forest would have you believe that there were two completely different processes operating at the same time when the operating point was at the knee of the curve. De Forest went on to make this closing statement in the portion of his lecture dealing with his two-electrode audion:

> "In other words, then, the two-electrode audion, with A and B batteries, was not primarily a 'valve.' And I have always objected to this misapplication of the name valve to the audion; a name which our British friends have from the first persisted with a stubbornness worthy of a better cause, in misapplying!"

By 1920 it was well known that the Fleming valve tube and the De Forest audion tube were identical. Even De Forest had admitted as much in 1906, but he claimed the big difference was the existence of a battery in his plate circuit. So how is it possible that one device was a valve and the other device was not? It is true that the use of an external battery determined how a two-electrode device functioned in a specific circuit, but it did not change the characteristic curve, which is what determined the designation of the device. There are three options for characterizing the type of device for a Hertzian wave detector, which is determined by the type of characteristic curve produced:

1. A symmetric detector configuration produces an I-V curve that is symmetric about the origin of the I-V axes.
2. An asymmetric detector configuration produces an I-V curve that is asymmetric about the origin.
3. A valve detector configuration produces a unipolar curve that displays a valve action.

De Forest's early flame detector with symmetric electrodes had a nonlinear but symmetric curve that required a battery to move the operating point to a location where there was a knee on the curve. De Forest's later flame detector with asymmetric electrodes had a unipolar response without a battery but it did not display a valve effect because it had a significant conductivity, no matter what polarity was used. De Forest's audion with asymmetric electrodes displayed valve action, but valve action was optional because there were two sensitive operating points with a "knee in the curve," one near the origin where there was valve action with little or no external battery required, and one near the saturation level where a significant battery voltage was required. Apparently, De Forest did not know, or at least did not let on that he knew his audion was a valve detector—and he never used it as such.

This classification is not just an exercise in semantics because the I-V characteristics of both De Forest's audions and Fleming's valve detectors displayed valve action, even though De Forest may not have realized it or observed it. By contrast, the flame detector that De Forest introduced in his AIEE lecture had a unipolar characteristic curve but did not display valve action. This is what distinguished his flame detector from his valve detector, and this is why De Forest's claim that he found the audion action in his flame detector turned out to be false. The lack of valve action in his flame detector was a result of the ionized gas that produced a significant conductivity for both battery polarities. Both types of detectors rectified Hertzian signals, but that does not mean an ionized gas detector operated the same way as a thermionic valve detector. In fact, a crystal detector, Fessenden's electrolytic detector, De Forest's flame detector, and Fleming's thermionic valve detector all operated on the principle of rectification, but all four had different physical embodiments with different operating characteristics and were considered to be different inventions.[75]

De Forest Misrepresented his Audion I-V Characteristic Curve—Again

The form of De Forest's characteristic curve of Fig. 40 is virtually identical to the curve he presented in his AIEE lecture (see Fig. 25). It was pointed out before that this form of the curve did not apply to his early audions because before his October 1906 lecture he connected the plate circuit of his audions to the positive pole of the filament battery electrode. When that happens, there is a significant Edison effect current that flows in the plate circuit when the battery voltage is zero. That is not the case for this I-V curve.

To illustrate this point, two different characteristic curves were measured by the author for an early manufactured two-electrode vacuum tube with a filament voltage of 5 volts. The plate current represented by the upper curve was measured when the negative pole of the plate circuit battery was connected to the positive pole of the filament battery, and the lower curve was measured when the plate circuit battery was connected to the negative pole of the filament battery. It turns out that the two I-V curves are parallel to each over the region where the two plate currents are linear (between 4 and 12 volts). In this range the two curves are offset by a voltage equal to the filament battery voltage, which in this case was 5 volts. However, the curves are not parallel over regions where one is linear and the other is nonlinear (below 4 volts and above approximately 12 volts).

For the plate circuit connection to the positive pole, the current is not zero when the applied plate voltage is zero. The plate current that flows in this case is the Edison effect current. Also, there is no lower knee in the curve for this case, contrary to what De Forest showed in his I-V curve. De Forest would have observed a second knee in the curve if he had applied a negative voltage to the plate, which would have revealed the entire characteristic curve. De Forest's I-V curve for his double-wing audion, with the connection to the positive pole of the filament battery, would have looked like the upper curve shown in Fig. 41. Since this curve is approximately linear between 0 and 12 volts, he would have had to apply a number of battery cells to reach an operating point where there was a knee in the curve.

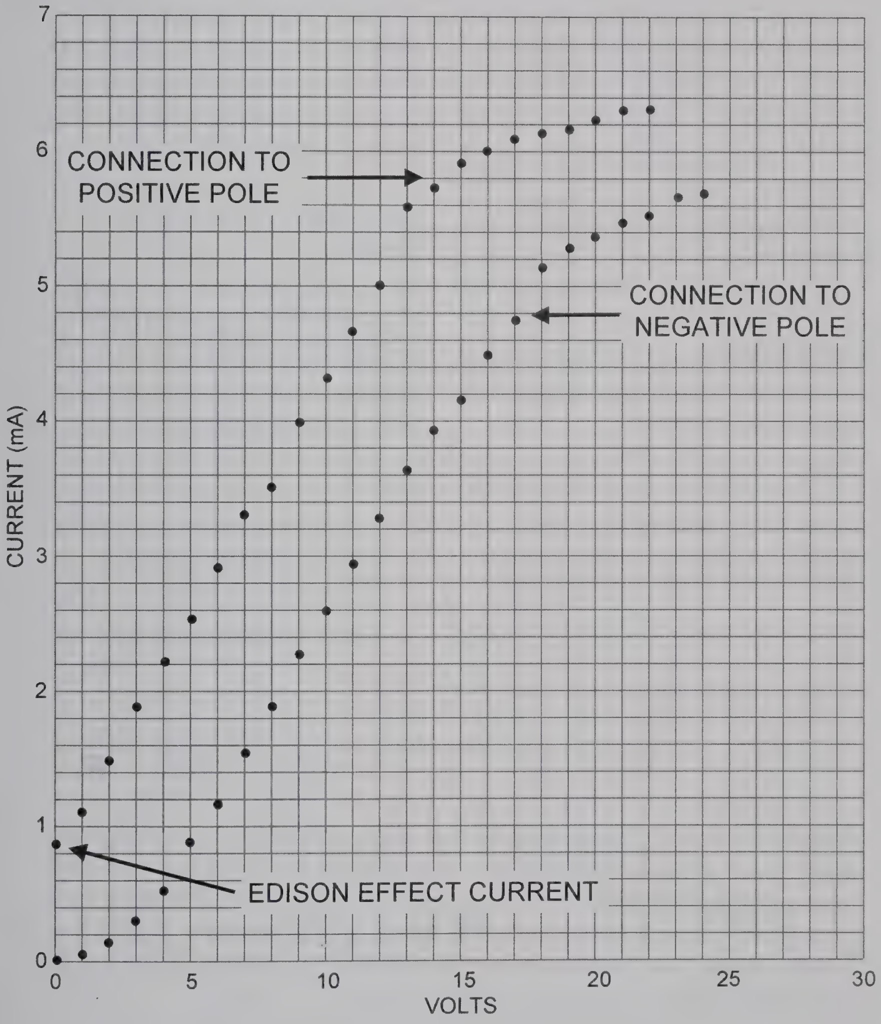


Fig. 41. Two characteristic curves for an early two-electrode vacuum tube with a filament voltage of 5 volts were measured: the upper curve shows the plate current for a battery in the plate circuit connected to the positive pole of the filament battery and the lower curve shows the current for the battery in the plate circuit connected to the negative pole. (Author's experimental results)

De Forest claimed that there were two knees in the curve for his audion and that he chose the upper curve. However, there would have been only one knee in the curve for his audion with the plate circuit connected to the positive pole of the filament battery. He had no option but to choose the upper knee as his operating point, and he never would have observed valve action by applying only positive voltages to the plate. That is why he claimed his detector was not a valve—even though it was. He just did not realize how to operate it as a valve, or perhaps he chose not to do so.

The shape of the lower curve is virtually identical to the I-V curves measured by Fleming for his valves, all of which had a plate circuit connection to the negative pole of the filament battery (see Fig. 42).[76] Fleming's detector had a strong valve effect for virtually all voltages applied with a negative polarity. This characteristic curve is very sensitive near the origin because contributions to the current from each oscillation are due primarily to the positive swing, while there are virtually no contributions from the negative swing. This is particularly true when the applied oscillations have a magnitude of a volt or more.

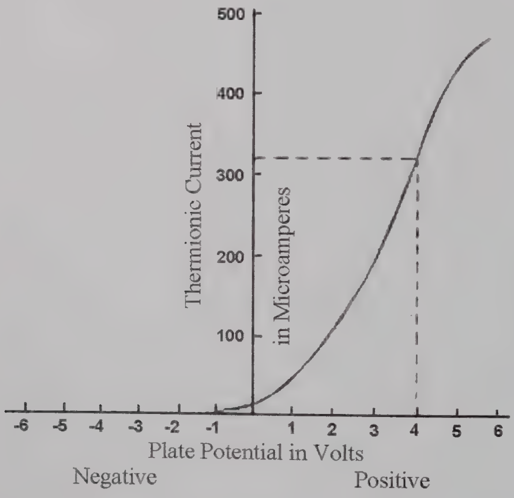


Fig. 42. This example of a characteristic curve for a Fleming valve with a connection to the negative pole of the filament battery had two knees in the curve, one near the origin of the axes where the curve began to display a valve effect for negative applied voltages, and the other near the top of the curve where the current began to saturate. (Univ. College London, Fleming Collection)

Summary and Conclusions

Summary

De Forest presented two major lectures in which he gave detailed accounts of how he invented his two-electrode audion. His first lecture was given to AIEE members on October 26, 1906, and the second lecture was given at the Franklin Institute on January 15, 1920. The accounts that he gave at the two lectures could not have been more disparate. The first account was fanciful and at times willfully deceptive. He claimed the genesis of his detector was the configuration with which Elster and Geitel experimented in 1882, and he supported this assertion by comparing his configuration with the Elster and Geitel configuration. However, the two configurations did not match, and it turned out that he surreptitiously altered the actual Elster and Geitel configuration in three significantly different ways to make their configuration match his. This claim was provably false, and most of the other claims he made were deceptive or misleading. A summary of these bogus claims can be found in the section of this paper entitled "Takeaway from De Forest's AIEE Lecture."

In the second lecture he gave at the Franklin Institution in 1920, De Forest ignored virtually all the claims he made in his 1906 lecture—with the notable exception of one in which he maintained his audion acted as a relay, or amplifier because of the battery he used in his external circuit. This time he claimed that he had discovered the audion principle in a flame detector that was documented in a patent application with a priority date that preceded the priority date of Fleming's valve patent. De Forest then claimed he perfected his invention by moving the two electrodes of his flame detector into an evacuated lamp bulb to make it a practical device. Finally, he claimed that he documented an audion detector bulb in 1905 consisting of an enclosure evacuated to the level of an ordinary incandescent lamp bulb in which he inserted a carbon filament heated to incandescence and one cold electrode. The dates of these claims are critical because De Forest admitted reading Fleming documents published early in 1905 describing the detector configuration and technical parameters that appeared in Fleming's patent. In the end, De Forest could not produce any documents that supported his claim that the priority date of his audion invention preceded the priority date of Fleming's valve.

The differences in the two accounts can be attributed to the results of a lawsuit that American Marconi filed against De Forest and Company in October 1914 for infringement of the Fleming valve patent owned by the Marconi Company that culminated in a trial in 1916. While De Forest was able to deceive an audience of scientists and engineers with bogus claims because they were unable to cross-examine him under oath, he could not deceive a trial judge in a court of law where proof is demanded in the form of sworn testimony and supporting documentation. Since there were no documents or potential witnesses to prove or support the claims he made at his first lecture, De Forest abandoned virtually all of those claims and developed a new account that he believed would withstand cross-examination in a trial. De Forest developed a new strategy for the trial based on a patent application for a flame detector that was accorded a priority date eight days earlier than the priority date of Fleming's first valve patent application.

Even though the judge in the 1916 trial rejected De Forest's argument based on the priority of his flame detector, he used the same argument in his 1920 account at the Franklin Institute. Exhibits submitted as evidence in the trial proved that De Forest revealed a two-electrode detector configuration contained within an evacuated bulb for the first time when he met with his attorney on November 24, 1905, a year after Fleming filed his patent application. A sketch of this configuration was revealed in this paper to support this assertion. The complete document and the events leading up to its discovery will be revealed in Part II.

Perhaps the most important difference between the accounts in De Forest's two principal lectures is how much he knew about the Fleming valve and when he knew it. In his 1906 lecture, he mentioned the Fleming valve only once in passing, and he marginalized it by saying that it was an insensitive device that was useful only for measuring larger signals that were available in the laboratory. He did not even reveal that Fleming had received a patent for his valve as a detector in wireless telegraphy. He was more candid in his lecture at the Franklin institute when he wrote, "At the period now under consideration, 1903–05, I was familiar with the Edison effect and with many of the investigations thereof carried on by scientists, Prof. Fleming among others." De Forest documented the fact that he had read Fleming's seminal document describing all details of his valve detector that had been published in March 1905. This document contained the schematic diagram of his Fleming valve detector that appeared in his patent application filed in November 1904.

Conclusions

1. Most of the claims De Forest made in his AIEE lecture were provably false or deceptive. The willful alterations he made to the Elster and Geitel experimental configuration in an attempt to make it match his audion, coupled with his failure to check their original reference is unforgivable. His misrepresentation of the I-V characteristics of his flame detector and audion bulb shows a surprising degree of incompetence.
2. The account that emerged from the 1916 trial was completely different from De Forest's lecture accounts. The trial account is most likely to be the most accurate one because it is based on sworn testimony and documentary evidence—including 31 pages of sworn testimony by De Forest himself.
3. The claims De Forest made in the account he gave at the Franklin Institute in 1920 were so different from his account in his AIEE lecture in 1906 and his testimony at the trial in 1916 that they are suspicious. Given the fact that there are no documents to support the claims in either of his two lectures, the account he gave under oath at the 1916 trial, with supporting documentation, is surely the most accurate.

A completely new and different account of De Forest's discovery/invention of his two-electrode audion will be presented in Part II, which will be submitted for publication in the 2024 edition of the *AWA Review*. Part II will contain many excerpts from the trial transcripts of sworn testimony by witnesses—especially by Lee De Forest—and copies of the actual exhibits that were introduced into the record in the 1916 trial.

Endnotes

1. "The Physical Society's Annual Exhibition of Apparatus," *The Electrician* (London), Vol. 66, Dec. 30, 1910, pp. 473–474.
2. A number of historians have used the "de Forest" form of spelling in their publications because they believe that was Lee's preference. Regardless of what his preference might have been, the "De Forest" spelling has appeared almost as often as the "de Forest" spelling in journals, textbooks, and other documents throughout the years. For example, the spelling that has appeared in newspapers and wire services throughout the years is predominately the "De Forest" form. Also, the legal spelling of Lee's many eponymous companies was De Forest with a capital De. Using the "de Forest" spelling in a document involving both the man and his eponymous companies results in a two-tier system in which the writer has to determine which spelling to use and the reader has to interpret: De Forest for his eponymous companies or de Forest for the man. Is it a De Forest audion or a de Forest audion? Who is being sued, De Forest or de Forest or both? Which spelling should appear in the endnotes: De Forest or de Forest, or does it depend on the spelling that is used in the article being cited? When using the de Forest spelling for the man, does the De Forest spelling (with a capital De that must be used at the beginning of every sentence) refer to the man or the eponymous company? For this paper, the choice was easy because the "de Forest" form of spelling does not appear even once in the *Federal Reporter* volumes documenting the legal opinions of judges or in the thousands of pages documenting the testimony, exhibits, and summaries in the 1916 trial referred to in Parts I and II. The De Forest form of spelling is used throughout this paper, regardless of the spelling that appears in the cited text.
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22. De Forest, AIEE lecture (1906), p. 720.
23. De Forest, Franklin Institute lecture, p. 2.
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About the Author

Eric Wenaas received his BSEE and MSEE in Electrical Engineering from Purdue University in 1963 and 1964, and his Ph.D. in Interdisciplinary Studies in Engineering at SUNY, Buffalo, in 1969. He is a past editor of the Antique Wireless Association publication, *AWA Review*, and has published over 40 articles on the early history of wireless communication and radio. He has also authored the book *Radiola*, a definitive history of RCA in the 1920s. He is currently the editor of the book review column for the *AWA Journal* and contributes book reviews to the IEEE publication, *Technology and Society*. He has studied the works of Lee De Forest for many years and has an extensive collection of his early audions, oscillions (high-power oscillators), and detector boxes.

Eric Wenaas

Giant Horn Antennas in Space Communications

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This article celebrates the 60th anniversary of the 1962 Telstar 1 satellite by highlighting the development of Bell Laboratories' giant horn antennas at Andover Earth Station in Maine and at Crawford Hill in Holmdel Township, New Jersey. The Telstar satellite relied on these and other ground antennas to communicate from orbit to Earth. Telstar allowed the first live broadcast of television images between the United States and Europe. Operational for only seven months, Telstar failed due to a high-altitude nuclear test conducted by the United States. The two horn antennas were used after Telstar failed for research and other satellite communications. The Crawford Hill antenna still exists, although it is not operating. It played a pivotal role in Project Echo, Bell Laboratories' 1960 satellite relay experiment, and in the 1965 discovery of cosmic microwave background radiation (CMBR) that permeates the universe, leading to two Nobel Prizes in Physics. The Andover horn antenna was dismantled in the mid-1980s, but Andover Earth Station continues to operate as part of Verizon's Satellite Solution Group.

Introduction

The space age commenced in 1957 when the Soviet Union launched its Sputnik 1 satellite. The United States followed with the Explorer 1 and Vanguard 1 satellites in 1958. Four years later, American Telephone & Telegraph Company's (AT&T) research arm, Bell Telephone Laboratories (Bell Laboratories), orbited Telstar 1, the world's first commercial telecommunications satellite. The technological jump that occurred between these first few satellites and those that followed in the early 1960s was gigantic. Sputnik 1 used radio tubes to operate a radio beacon. Explorer 1 and Vanguard 1 used transistors, becoming the world's first solid-state satellites. Telstar 1 applied developments in traveling-wave tube (TWT) technology, initially developed in radar applications, to enable global television. Together, these early satellites proved reliable telecommunications could take place in the harsh environments of space. These advances later contributed to the Apollo missions and established many of the methods that enabled radio and television signals in space, helping to accomplish man's first landing on the moon and other space explorations.

This article focuses on the Bell Laboratories' giant horn antenna at the Andover Earth Station in Maine (approximately 90 miles northwest of Portland) and on its predecessor, the microwave horn antenna at Crawford Hill in Holmdel Township, New Jersey (approximately 35 miles southeast of Newark).

Other early antennas and discoveries are also highlighted in this survey of some early milestones in space communication antenna development.[1] This article is organized chronologically into sections that roughly correspond to the development of the two horn antennas and other notable historic developments.

PART I. SPUTNIK, EXPLORER, AND VANGUARD

The launch of Sputnik 1, on October 4, 1957, publicly kicked off the political and scientific competition between the United States and the Soviet Union to demonstrate leadership and control in space.[2] On November 3, 1957, the Soviet Union launched a second, heavier satellite, Sputnik 2, carrying a dog, Laika (also spelled Layka).

The launches of Sputnik 1 and Sputnik 2 led the U.S. government to focus on and to consolidate its space exploration programs. That summer, Congress and President Dwight D. Eisenhower created the National Aeronautics and Space Administration (NASA), which was officially formed on October 1, 1958.[3] Sputnik 1 and 2 relied on radio tube technology to transmit radio tracking signals back to Earth. Neither Sputnik satellite was interactive in the sense of receiving and retransmitting radio or television programming signals to and from the ground. Sputnik 2 did transmit life signs from Laika as well as its radio tracking signals and telemetry information. On January 31, 1958, the U.S. Army launched Explorer 1, and Vanguard 1 followed on March 17, 1958. Both Explorer 1 and Vanguard 1 used new transistor technology and sent telemetry information and scientific measurements back to Earth ground stations.

American government inter-departmental competition for leadership in rocket design and scientific research created considerable confusion in the 1950s. The military initially envisioned that it could carry a nonmilitary satellite into orbit by using modified rocket designs and different payload designs, but the Army and Navy each pursued their own design concepts.[4]

The Soviet Union's Sputnik 1 surprise caused the U.S. military and President Eisenhower to change direction.[5] The U.S. Department of Defense quickly authorized the U.S. Army to proceed with its original proposal for the Explorer Program (Project Orbiter). President Eisenhower then permitted the Army to adapt its military rockets for nonmilitary use, an approach formerly denied to the Vanguard Program in an effort to keep the U.S. space effort free from military overtones.[6]

In the end, military rockets with minor modifications launched Explorer 1—in contrast to Vanguard 1, which was launched by a specially designed research rocket that was conceptually independent of military involvement. The Navy's global tracking system of fourteen interferometer stations, Minitrack, designed by the Naval Research Laboratories (NRL) as part of the Vanguard Program, successfully tracked the Sputnik, Explorer, and Vanguard satellites, making Minitrack the major tracking system for most U.S. scientific satellites.[7]

By 1960, NASA was in charge of civilian launch services, yet its track record was not good, and payloads faced significant risk of destruction on the launch pad. During 1958 and 1959, fifteen launches (excluding tests) were attempted; only three were successful, with four additional launches partially successful. In 1960, out of ten attempts, only five were successful. This 50/50 probability of success started to improve in 1961, but only in 1962 did launch success rates start to exceed ⅔ probability of success.[8] This meant that commercial interests faced a considerable financial risk that the payload might be lost with each launch.

PART II. ECHO AND TELSTAR

AT&T and Telecommunications Capacity

AT&T and the Bell System began offering commercial transatlantic telephone services in 1927. Approximately 11,000 overseas calls were made that year using landlines in the United States and Europe that were linked by radio to span the ocean. In 1956, the first transoceanic submarine telephone cable linked the United States to the United Kingdom. Approximately 250,000 overseas calls were made in 1957, and other cables were being laid. By 1961, the yearly volume of overseas calls surpassed 4.3 million. Just as the demand for overseas telephone service was expanding, the demand for overseas television channels was growing. Although the Bell System operated more than 600 telephone-grade circuits for overseas communications, forecasts anticipated exploding demand, with capacity demands projected to double by 1965 and reach more than 16 times by 1980. The projected demands of 1980 would need 50 undersea cables. AT&T concluded that microwave radio systems could offer a solution. Since 1951, AT&T had been operating and expanding its "Long Lines" relay network of microwave radio towers across the United States. A special application of microwave technology might hold the answer to cross an ocean, in space using satellites.[9]

Satellite Radio Tracking[10]

Communication with satellites moving through space at thousands of miles per hour requires the use of radio tracking. Finding the satellite is the first step in communicating with it. The origins of radio tracking begin with Bell Laboratories' engineer Karl Janksy, who discovered and followed celestial radio noise sources using directional antennas in 1932. Grote Reber followed, building the first paraboloidal radio telescope in his backyard in 1937. Overseas, Sir Robert

Watson-Watt was tracking aircraft in Great Britain with primitive radar as early as 1935, and the concept of radio echoes had been noted decades earlier. By the mid-1930s, five electronic tracking schemes had some potential for tracking satellites:

- Radar, which required no signal source on the satellite.
- Dish tracking, using a Reber radio antenna dish, which necessitated a satellite-borne transmitter.
- Triangulation, using radio-direction finders, which also required a signal source on the satellite.
- Doppler analysis of the radio signals received from a moving source, which, although recognized in 1937, was not appreciated for its value in tracking.
- Radio interferometry, using two receiving points and the comparison of the phases of the signals received separately by each.

German engineers at Peenemunde during World War II were the first to use radio guidance (not tracking). Their method used VHF transmitters to lay down a lobed antenna pattern to improve azimuth guidance during a few V-2 flight tests. The technique was not employed during operational use, and it bears only a superficial resemblance to later satellite-tracking interferometers.

The Minitrack Network was the first U.S. satellite tracking network to become operational, in 1957. It was used to track the Sputnik, Vanguard, and Explorer satellites and other early space efforts. Minitrack was the predecessor of the Spacecraft Tracking and Data Acquisition Network (STADAN) and the Manned Space Flight Network (MSFN). By the time early commercial satellite development efforts were underway circa 1960, such as Project Echo and Telstar, American Minitrack stations were operating and available for use, with the worldwide network of stations expanding each year.

Project Echo

The U.S. Air Force sponsored a meeting on the development of communications satellites in July 1958. John R. Pierce from Bell Laboratories (see Fig. 1) presented on the topic of passive satellite relays. He described how a reflective orbiting body could be used to bounce transmissions from one point on Earth to another. William H. Pickering, director of the Jet Propulsion Laboratory (JPL), was in attendance. JPL had little interest in communications satellites, but they foresaw that additional ground-support equipment would be

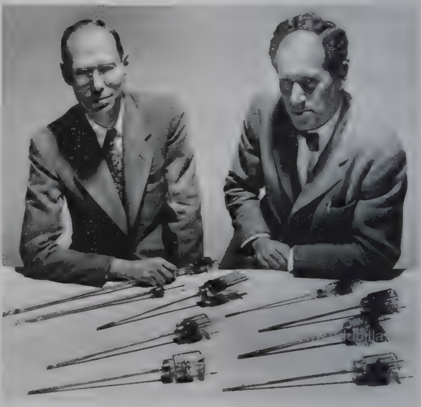


Fig. 1. John R. Pierce (left) and Rudolf Kompfner (right) with an array of Traveling Wave Tubes. (Courtesy Bell Laboratories)

needed to conduct the passive satellite communications experiments, and this equipment could be applied to tracking and communicating with space probes. Pickering suggested that JPL antenna facilities at Goldstone Dry Lake in the Mojave Desert could be used as a ground facility for Pierce's satellite experiments. JPL agreed to build a polar-mounted antenna 85 feet in diameter at Goldstone for this purpose.[11]

Three months later, in October 1958, Pierce and Bell Laboratories' engineer Rudolf Kompfner (see Fig. 1) presented an experimental concept for observing atmospheric refractive effects. The idea of using an inflatable reflective balloon as a satellite originated with William J. O'Sullivan (see Fig. 2) at NASA's predecessor NACA, the National Advisory Committee for Aeronautics, during a 1956 meeting of the Upper Atmosphere Rocket Research Panel. The panel was designing experiments for the U.S. Army to put on captured German V-2 rockets that needed payloads for experimental launches.[12] Pierce's and Kompfner's concept also focused on using reflective balloons as satellites. They sought to extend research efforts that could lead toward using satellites in transoceanic communications. They presented their paper to the National Symposium on Extended Range and Space Communication on October 6–7, 1958 where they proposed launching balloon satellites as passive communications reflectors.

As the program came into existence, W. C. Jakes (see Fig. 3) was named as project leader over an ad hoc group of people from many disciplines throughout the organization, but especially from the Electronics and Radio Research Department. The leadership team comprised

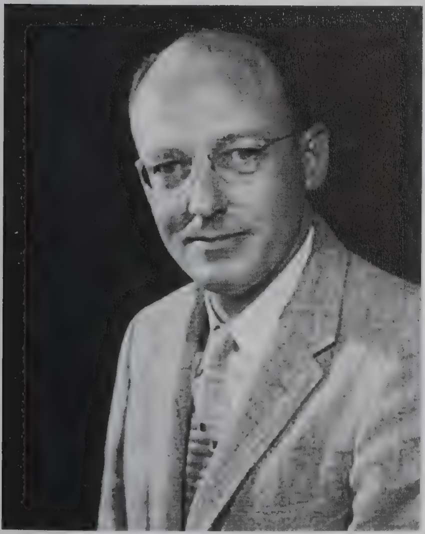


Fig. 2. William O'Sullivan. (Courtesy Bell Laboratories)

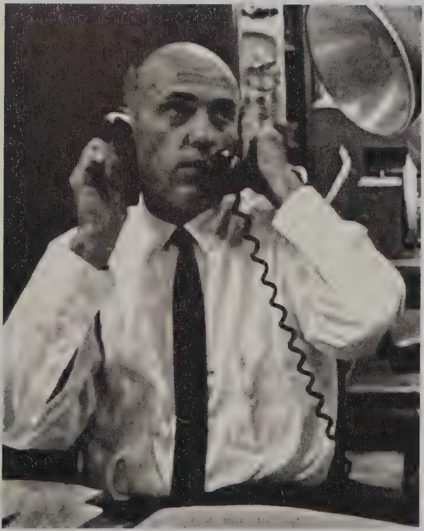


Fig. 3. W. C. Jakes. (Courtesy Bell Laboratories)

several dozen people. Bell Laboratories cooperated with the newly forming NASA, JPL, NRL, and others in creating the communications systems for the Echo satellite.[13]

Coincidentally, as NASA formed, JPL was transferred from the U.S. Army to the new agency. Project Echo, NASA's first communications satellite project, was officially laid out on January 22, 1959 at a meeting with representatives from NASA, JPL, and Bell Laboratories. A launch was targeted for September 1959.[14] NASA's program responsibilities now included developing and supporting experimental communication satellites. On August 12, 1960, NASA launched Echo 1 for Bell Laboratories as part of its civilian research support (see Fig. 4 and Fig. 5). Echo 1 was the world's first passive satellite that reflected real-time voice radio signals back to Earth. The Echo 1 satellite was a 100 foot diameter aluminized-polyester balloon that inflated after reaching orbit. It provided "good" quality two-way voice links between Bell Laboratories in Holmdel, New Jersey, and NASA's JPL facility in Goldstone, California.[15]

Bell Laboratories conceived Project Echo as an experimental mission. The objective was to test new technologies for future missions, testing limits in aerodynamics, satellite shape and size, construction materials, temperature control, and satellite tracking.[16] The Echo 1 satellite had the following objectives: (i) observe and measure atmospheric

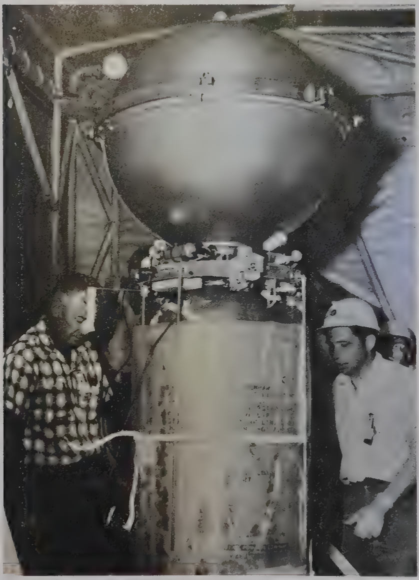


Fig. 4. Technicians preparing the Echo 1 satellite payload before launch. (Courtesy NASA)

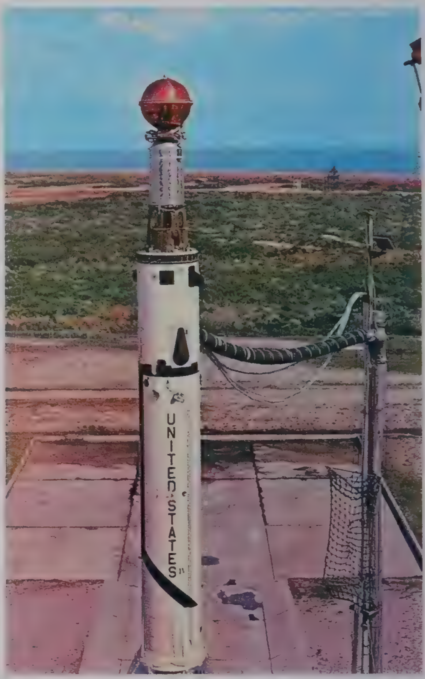


Fig. 5. U.S. Air Force postcard of Echo 1 in its canister atop a Thor-Delta rocket prior to launch. (Authors' collection)

drag, (ii) passively reflect ground-based transmissions, (iii) demonstrate two-way communications, (iv) demonstrate commitment to an American space program that included civilian participation, and (v) provide precedent for the overflight of other nations by satellites.[17] All of these objectives were met. Major accomplishments included:[18]

- First demonstration of voice transmission via the satellite of President Eisenhower's prerecorded message sent from JPL to Bell Laboratories.
- First two-way audio transmission between JPL and Bell Laboratories of prerecorded messages between President Eisenhower and Senator Lyndon Johnson.
- First two-way live voice transmission between W. C. Jakes of Bell Laboratories and P. Tardini of JPL.
- Voice reception from NRL.
- Two-way live voice transmissions with JPL using standard telephone lines connected to a satellite circuit.
- Telephone conversation between F. R. Kappell (president of AT&T), L. DuBridge (president of JPL), and J. B. Frisk (president of Bell Laboratories) talking between California and the east coast.
- Demonstration of a facsimile picture transmission from NRL.

The Echo 1 satellite was 100 feet in diameter and weighed 135 pounds (see Fig. 6). It was constructed of Mylar plastic film, only 5 ten-thousandths of an inch in thickness (approximately 500 millionths of an inch in thickness). In order to reflect radio waves, the mylar film was coated with an extremely thin layer of aluminum in a vacuum chamber. The aluminum was so thin it contributed no structural strength to the sphere. This was evident after the Echo 1 sphere had been in orbit for some time when it exhibited wrinkling, changing its shape and losing volume, rendering it less acceptable as a communications reflector (see Fig. 7).[19]

The construction of Echo 2 tried to compensate for Echo 1's shortcomings.

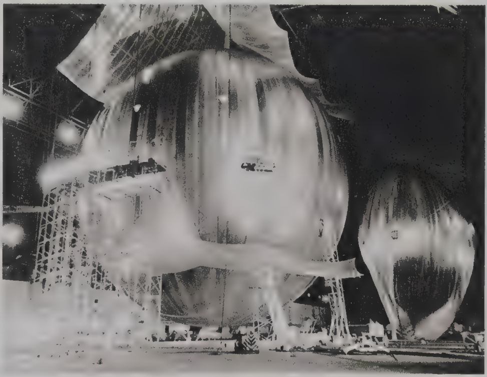


Fig. 6. Echo satellites being tested for tensile strength in a dirigible hangar. (Courtesy NASA)

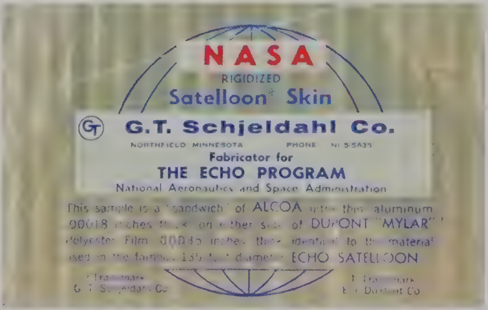


Fig. 7. Sample of Echo 1 "satelloon" rigidized Mylar skin fabricated by G. T. Schjeldahl. (Authors' collection)

It was larger, at 135 feet in diameter, and weighed about 500 pounds. Echo 2 was made of a laminate, a combination of two layers of aluminum foil and one of Mylar, with a total thickness of 750 millionths of an inch, 50 percent thicker than Echo 1. The result was appreciably stiffer because of the presence of the two layers of aluminum foil, and the satellite surface did not wrinkle as pressure dropped. The increase in weight necessitated the use of a larger launch vehicle. Echo 2 launched in January 1964. The unfolding and inflation of the two Echo satellites each occurred at an altitude of more than 200 miles, approximately 186 seconds after launch.[20] Additional Echo satellites were built but not deployed; one is on display at the Smithsonian Air and Space Museum Udvar-Hazy Center (see Fig. 8).

As a passive satellite, Echo 1 required high-power transmissions from Earth to return detectable signals. In contrast, active satellites could receive, amplify, and retransmit signals, and were capable of working on much lower incoming signal levels. The U.S. military produced Courier 1B in October 1960, the world's first interactive satellite. It contained repeaters capable of converting frequencies for uplink and downlink signals; however, it was only an experimental device.[21] Yet, based on Echo 1's success, Pierce envisioned a complete network of ground stations and satellites that could connect with any point on Earth's surface. His plan encompassed 25 ground stations and 55 active satellites in orbits up to 7,000 miles, with 40 satellites placed in a polar orbit and 15 placed in equatorial orbits. This strategy would allow satellites to connect any two points on almost 100 percent of the Earth's surface.[22]

Project Echo was a great success and millions of people saw it reflecting and moving across the night sky. It was on the front page of virtually every major newspaper and magazine; it was covered in television news; and it could be seen by the naked eye as it passed overhead.[23] AT&T and the Bell System featured it in their advertising (see Fig. 9). Echo 1 made the public aware of the possibilities of satellite communications and boosted morale, following America's many mishaps and failed attempts to launch successful missions

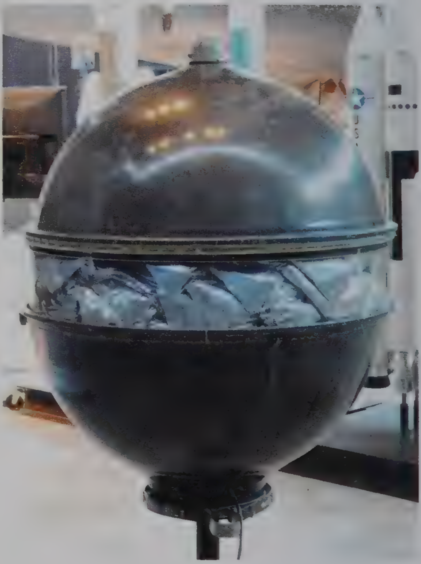
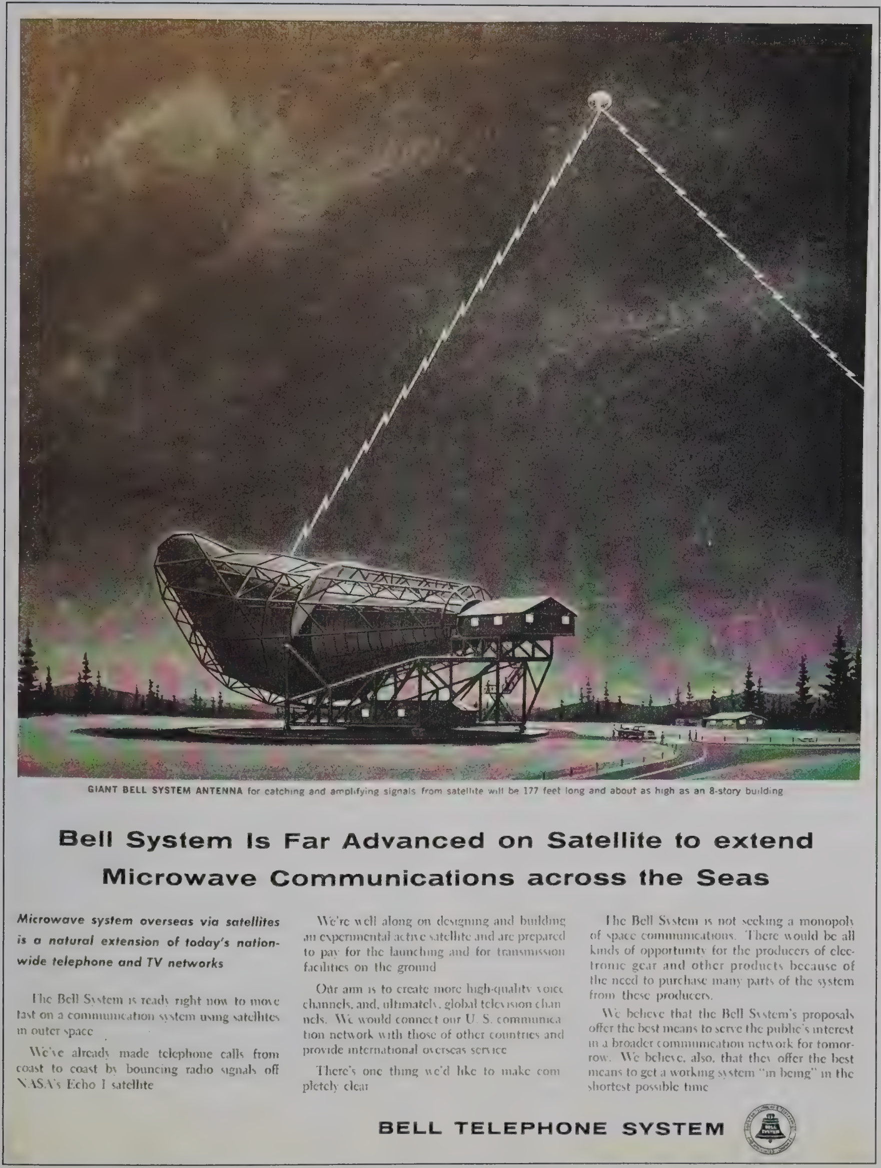


Fig. 8. A spare Echo communications satellite in its 26 inch diameter canister with the satellite still folded inside for deployment; on display behind the Space Shuttle Discovery at the Smithsonian Air and Space Museum, Udvar-Hazy Center. (Authors' photo)

into space. Critically, Project Echo was not operating in isolation. It followed Pioneer 1 and Project Score in 1958 and the Courier 1B satellite in 1960. Pioneer 1, also known as Able 2, was NASA's first space probe. Project Score was the U.S. Army's Signal Communications by Orbiting Relay Equipment, which provided the first broadcast by a satellite, a recorded message of a human voice in



GIANT BELL SYSTEM ANTENNA for catching and amplifying signals from satellite will be 177 feet long and about as high as an 8-story building

Bell System Is Far Advanced on Satellite to extend Microwave Communications across the Seas

Microwave system overseas via satellites is a natural extension of today's nation-wide telephone and TV networks

The Bell System is ready right now to move fast on a communication system using satellites in outer space

We've already made telephone calls from coast to coast by bouncing radio signals off NASA's Echo I satellite

We're well along on designing and building an experimental active satellite and are prepared to pay for the launching and for transmission facilities on the ground

Our aim is to create more high-quality voice channels, and, ultimately, global television channels. We would connect our U. S. communication network with those of other countries and provide international overseas service

There's one thing we'd like to make completely clear

The Bell System is not seeking a monopoly of space communications. There would be all kinds of opportunity for the producers of electronic gear and other products because of the need to purchase many parts of the system from these producers.

We believe that the Bell System's proposals offer the best means to serve the public's interest in a broader communication network for tomorrow. We believe, also, that they offer the best means to get a working system "in being" in the shortest possible time

BELL TELEPHONE SYSTEM

Fig. 9. Bell Telephone advertisement featuring Project Echo. (Author's collection)

space. Courier 1B was a joint program of the U.S. Defense Department under ARPA, the Advanced Research Projects Agency, and the U.S. Army Signal Research and Development Laboratory, that demonstrated the concept of a satellite retransmitting signals received from Earth. Bell Laboratories participated in both Project Score and Courier. In contrast, Project Echo was essentially a commercial effort to enter space and an effort to test and demonstrate America's capabilities and technical knowhow in telecommunications.[24]

Given the relative paucity of available tracking stations worldwide, Robert Mackey of the Goddard Space Center proposed enlisting volunteers to help maximize the tracking capabilities for the satellite. Ultimately, twelve NASA tracking stations around the world participated, plus over 48 volunteer "Moonwatcher" visual and photograph stations, and hundreds of amateur radio operators solicited by the American Radio Relay League.[25]

Bell Laboratories and AT&T both celebrated and marketed the success of Project Echo. An artist's drawing of the Holmdel horn antenna in the night sky with a light trail from the Echo satellite appeared on the cover of AT&T's 1960 annual report to shareholders. They promoted the companies by featuring the Echo satellite and Holmdel antenna in advertising, as well as educating the public about the progress of American telephone and communications technology. They also produced pamphlets, postcards, records, and educational films sold to schools. "The Big Bounce" film documentary contains substantial film footage and information about Project Echo (see Fig. 10). The "Sounds From Space" 33⅓ LP record includes excerpts of signals received from several satellites and space probes, including Sputnik, Vanguard, Explorer, Pioneer, and Score as well as signals and voice messages from Echo 1 received at Holmdel (see Fig. 11). The U.S. Post Office issued several first

A 14-minute Technicolor film report on Project Echo and other space communications studies.
THE BIG BOUNCE

Fig. 10. Promotional brochure for "The Big Bounce," an educational film produced by Bell Laboratories about Project Echo. (Authors' collection)

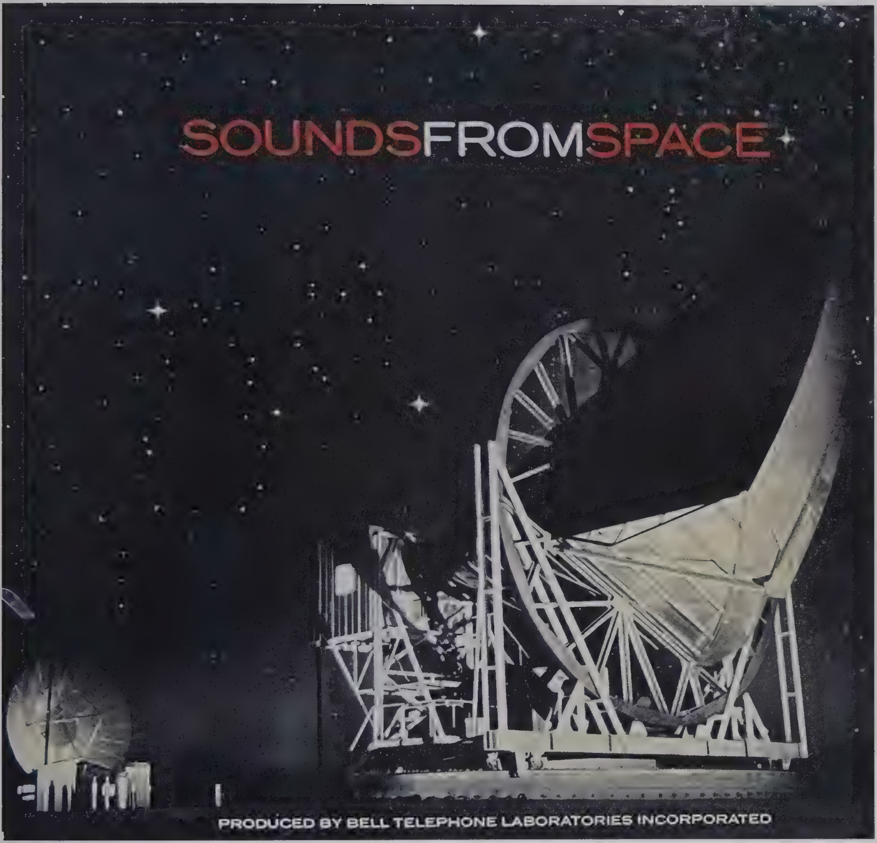

SOUNDSFROMSPACE
PRODUCED BY BELL TELEPHONE LABORATORIES INCORPORATED

Fig. 11. "The Sounds From Space" LP record produced by Bell Laboratories, 1960, featuring the Holmdel horn antenna. (Authors' collection)

day covers for its commemorative stamp celebrating Project Echo.

The positive publicity laid the groundwork, both with the public and politically, to support the much larger Telstar project. Within a year of Project Echo, several multinational firms such as RCA, General Electric, ITT, and others announced their entrance into space research and operations. Satellites were quickly becoming a "cutthroat business" and a "race to install the great cable in space" as an alternative to landline and undersea cable communication routes.[26]

Telstar

Bell Laboratories designed and built "Telstar," an experimental active communications satellite, at its own expense. Many of the same people who developed Echo 1 contributed to Telstar.[27] The leadership team at Bell Laboratories included: Alton Dickieson (executive director, Transmission Development Division), Eugene O'Neill (project director), Irwin

Welber (test conductor, Andover), Williams Jakes (test conductor, Andover), Robert Shennum (head, Satellite Design Department), and H. Nelson Upthegrove (head, Satellite Launch Operations). The leadership team included the Long Lines Department at AT&T, NASA headquarters, and Goddard Space Flight Center.[28]

Approximately 600 telephone company personnel plus personnel from 800 subcontracting firms worked on the project (see Table 1).[29] This was a huge leap from Project Echo, which had been accomplished with a Bell Laboratories' staff of approximately three dozen people. The work environment on Telstar was a significant departure for those who were used to a slower, orderly, research-based pace that pursued quality and durability rather than shifting tasks, breakneck speed, and pell-mell competition between teams as the project met tight deadlines and stricter budgets. The complexity and scale of Project Telstar was vast compared to Project Echo. Telstar itself had 15,000 parts, plus modifications at Holmdel, and the construction of a giant antenna system at Andover.[30] Ultimately, Bell Laboratories built six Telstars as prototypes to test the overall system, and two of these would eventually launch.[31]

NASA provided launch services and some tracking and telemetry. Despite claiming that Telstar was a joint government/industry project with AT&T, AT&T reimbursed NASA for its Telstar-related expenses of approximately $3 million per launch; thus, AT&T carried the full costs of the project. NASA also republished many of the results first issued in various Bell Laboratory professional publications as NASA publications. Further, NASA obtained patent rights to any inventions stemming from the Telstar experiments.[32]

Table 1. Staffing for Project Telstar. (Source: The Bell Systems Project Telstar.)

Staffing for Project Telstar	
Bell Laboratories	400
Western Electric	105
AT&T Headquarters	20
AT&T Long Lines Department	15
New England Tel. & Telegraph	46
Direct Personnel	586
Outside Contracting Firms	800
Total	1,386

AT&T began considering the use of artificial satellites as early as 1954, but Sputnik 1 prompted an acceleration of its research efforts.[33] The goals of Project Telstar included testing:[34]

- broadband satellite operations using up to 60 channels of telephony, data transmission, and single-channel television,
- equipment reliability after launch and in the harsh environment of space,
- measurements of radiation levels in space,
- knowledge about ground tracking methods, and
- ground stations.

The Telstar satellite reflected entirely new engineering concepts: a beach-ball-sized sphere with solar cells for power and a single antenna. The Telstar satellites incorporated recent advances in TWT technology. The satellite was 34.5 inches in diameter with a height of 44 inches, and it weighed 170 pounds (see Fig. 12). The satellite rotated at 200 revolutions per minute. It had a capacity of 600 one-way voice circuits or one television channel plus 60 two-way voice circuits, all relying on one 50 MHz bandwidth double conversion repeater. The transmitter circuit was entirely solid-state, except for the TWT amplifier. The receiver operated at 6.39 GHz and the transmitter operated at 4.17 GHz. The antenna system operated through 48 ports equally spaced around the sphere, and Telstar received through 72 ports.[35] A single, one-way broadband amplifier and a simple omnidirectional antenna with a circular polarization issued transmissions that radiated from the spin-stabilized satellite.[36] Telstar used state-of-the-art solid-state technology, employing 2,528 semiconductors: 1,064 transistors and 1,464 diodes.[37] Unlike

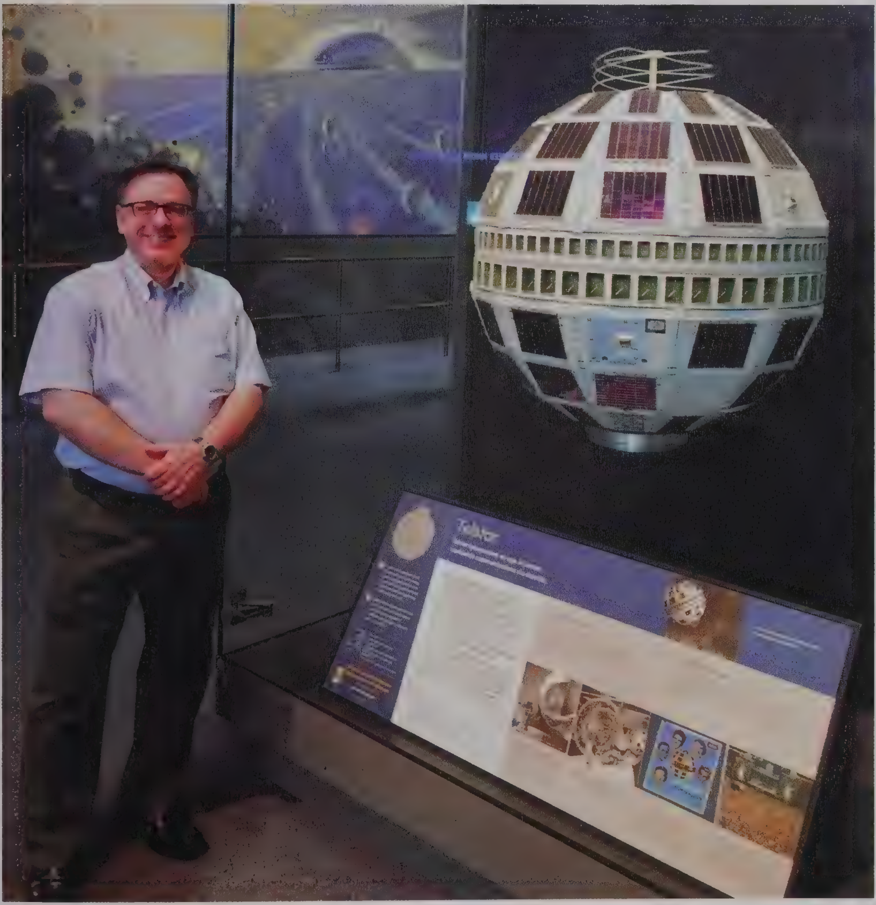


Fig. 12. The author with a Telstar satellite on display at the Smithsonian Air and Space Museum in 2019. (Authors' photo)

Echo 1, which involved the transmission of only one two-way telephone conversation at a time, Telstar's broadband signal was capable of carrying hundreds of voice or data channels or a single live television signal.[38]

The TWT was a major advance in technology. It is an electronic vacuum tube microwave device that acts as a high-power microwave amplifier. It was the most critical component of the satellite. TWTs are a class of linear beam vacuum tube that amplifies the radio wave by absorbing power from a beam of electrons as it passes down the tube, thereby amplifying radio frequency signals in the microwave range.[39] These commercial helix TWTs were used in early microwave radio relays in the United Kingdom, France, and the United States. By the late 1950s, new TWTs developed by Bell Laboratories began replacing the earlier triodes used in Bell System telephone circuits since they could carry at least 1860 telephone channels. The Western Electric 444A was used in these systems. Both Pierce and Kompfner at Bell Laboratories had significant experience with TWTs, and they thought that TWTs offered an optimal means for Telstar to demonstrate signal amplification in an active satellite.[40]

Dr. Max Bodmer (a benefactor of the Antique Wireless Association), a researcher at Bell Laboratories, designed a TWT for use in the Telstar satellite. Bodmer's team concluded that TWTs offered "long life and high reliability" for the conditions in space, and "the broad bandwidth and high gain is such that only a single tube was necessary."[41] They spent more than two years at Bell Laboratories producing the M4041 TWT that was used in the Telstar satellite, the first TWT used in space. The team implemented techniques for building super-clean tubes, design failure mechanisms, and developed a tube that could survive the rigors, shock, and vibration of a space launch.[42] The M4041 TWT produced signals with extremely little electron beam leakage. It was so precise that only the satellite's telemetry circuits required special shielding from the TWT.[43] The M4041 had a lifetime of 100,000 hours, ten times greater than the 444A, with more than twice the power output efficiency (see Fig. 13 and Table 2).[44]

Telstar operated in low elliptical orbits of 3,000 to 7,000 miles. It required a global network of six tracking facilities to receive the satellite's signal, which was generated by only 2.25 watts of power. Less than one billionth of this signal reached the ground.[45] A special, highly sensitive antenna system had to be designed and built to receive this faint signal.

Table 2. Traveling Wave Tube characteristics.
(Source: Minenna et al., 2018, pp. 14, 22)

Travelling Wave Tube Characteristics		
Western Electric	**444A**	**M4041**
Frequency (GHz)	5.9–6.4	3.7–4.2
Power Out (W)	5	2
Gain (dB)	30	40
Efficiency (%)	23	<10
Lifetime (hours)	10,000	100,000

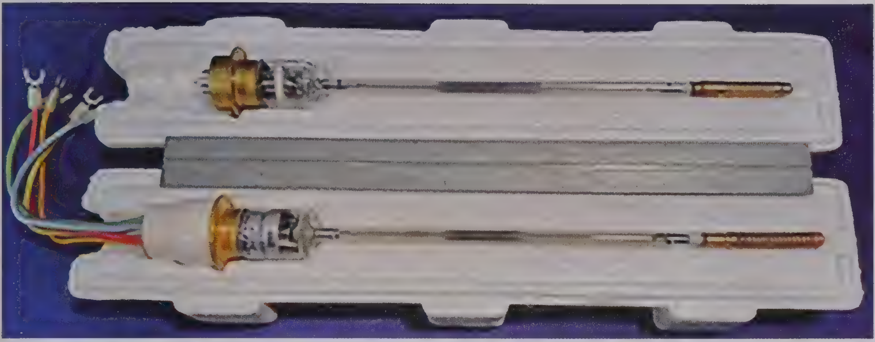


Fig. 13. A Max Bodmer experimental traveling wave tube from Bell Laboratories (top tube, glass marked BP215, base etched 229), predecessor to the model M4041 used on Telstar; and a Western Electric 444A production model TWT (bottom tube), the first TWT to be shipped for customer use beginning in 1959, with a 12 inch steel ruler for scale. (Authors' collection)

Bell Laboratories constructed its own signal-receiving facility near the small logging town of Andover, Maine, population of approximately 800.[46] This facility, located on a thousand-acre hilltop owned by AT&T, housed a large horn antenna within a flexible radome (a structural, weatherproof enclosure that protects a radar antenna) that was approximately 210 feet in diameter, the world's largest. NASA would later use Andover on a contract basis for the Relay satellite system. Telstar also operated with international agreements for the use of facilities in Canada, Great Britain, France, Germany, and Italy.[47]

Telstar 1's telemetry system transmitted once every minute. The satellite signaled the TWT's heater voltage, current, accelerator current, collector current, and tube temperature as measured at the output waveguide flange. The data was received at Andover and showed the TWT performed perfectly.[48]

The Telstar launch was an internationally anticipated event. Telstar had an elliptical orbit that was inclined up to 45 degrees. Its location moved with each orbit relative to the fixed geographic locations on Earth.[49] Consequently, transatlantic signals were limited to twenty minutes in each 2.5-hour orbit, when the satellite was over the Atlantic Ocean. Telstar relayed its first non-public international television signals between France and the United States on July 11, 1962, and its first public television signals on July 23. Major networks (NBC, CBS, ABC, CBC, BBC, and Eurovision) transmitted the television broadcast that included a variety of content.[50] Telstar broadcast live television in both black and white and in color. It also relayed 400 transmission sessions including multi-channel telephone, telegraph, facsimile, and television signals (see Fig. 14, Fig. 15, and Table 3).[51]

Telstar was a huge international success. It received front-page newspaper coverage and led television news coverage around the world. Several

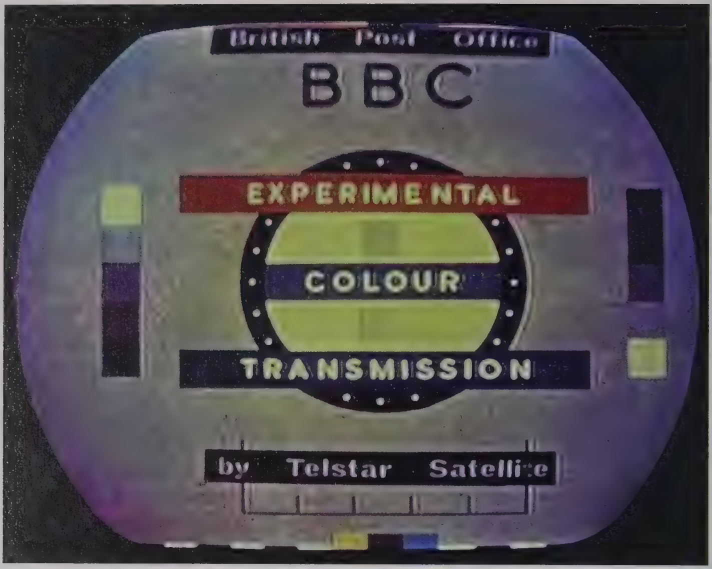


Fig. 14. Photo of British Post Office/BBC color television test signal broadcast via Telstar. (Authors' collection)

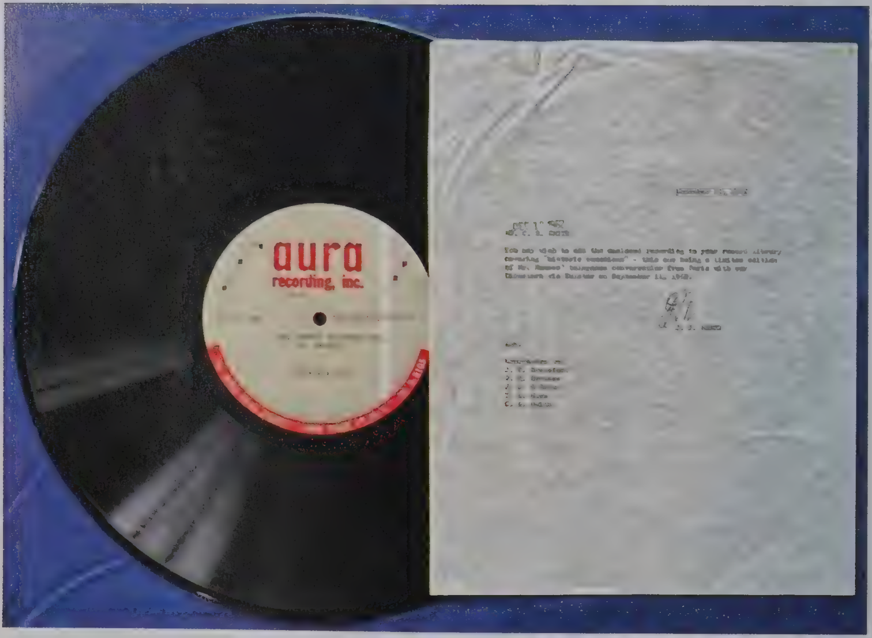


Fig. 15. One of six recordings (33 ⅓ single-sided microgroove, Aura Recording, Inc., with transmittal letter) of a Telstar telephone call from Paris to New York between H. I. Romnes, president of Western Electric, and Western Electric directors, Sept. 11, 1962. (Authors' collection)

Table 3. Summary of Telstar 1 experiments, performed July 10, 1962, through Nov. 22, 1962. The data tests ranged from 60 wpm teletype to 62,500 cps and 875,000 bps data transmission. (Source: "Summary of Telstar Demonstration-Tests," Project Telstar Press Relations Binder, D. Manahan, 1962.)

Summary of Telstar 1 Experiments		
Tests for International Carriers:		RCAC, ITT, Western Union, Press Wireless, French Cable, General
Telegraph and teletypewriter	68	
Data tests up to 2000 bps	26	
Facsimile	31	
Telephone test of Echo suppressor	1	
Total International Carriers	126	
Telephone Calls	123	U.S., Foreign
Data Tests (AT&T, GPO, French PT)	66	U.S., UK, France
Black & White U.S./European TV	42	U.S., Canada, UK, Europe
U.S. Department of Defense Tests	32	Mobile Ground Stations Nutley, NJ
Company Data Demonstrations	14	For 11 Business Machine Mfrs.
Facsimile	9	U.S., UK, France
Color Television	5	U.S., UK
Holmdel Satellite Communications	5	Light Ground Commun. Systems
Total	548	

countries issued first-day covers for commemorative postage stamps. The Telstar achievement symbolized Bell Laboratories' and AT&T's leadership in telecommunications research. Today, Telstar is still the best-known satellite associated with the beginning of live television transmitted via satellite.[52]

PART III. THE GREAT HORN ANTENNAS

Ground Stations for Project Echo

Project Echo relied on two ground stations: JPL's Goldstone facility and Bell Laboratories' Holmdel facility located on Crawford Hill in Holmdel, New Jersey (see Fig. 16). Bell Laboratories had acquired 473 acres of land in the rural township of Holmdel in 1929, approximately 35 miles from its Murray Hill, New Jersey facilities. The rural site had become the center of microwave transmission research and the location for many large experimental antennas. Approximately one mile north of the Holmdel laboratories, Bell Laboratories had also acquired a small flat-topped rise

COMMUNICATION VIA SATELLITE

Conception of telephone transmission via a space satellite. Bell Telephone Laboratories will take part in the National Aeronautics and Space Administration's "Project Echo" to test whether satellite transmission will be feasible for transoceanic communication. In the foreground is the "horn antenna" designed at the Labs and now being built at Holmdel, N. J. The antenna at the left will be located at the Jet Propulsion Laboratory at Goldstone, California. The satellite will be made of plastic, 100 feet in diameter.

Fig. 16. Educational poster promoting Project Echo showing the Jet Propulsion Laboratory's Goldstone and Bell Laboratories' Holmdel/Crawford Hill antennas bouncing a signal off the Echo satellite. (Authors' collection)

about 500 feet above sea level within sight of the ocean. By the late 1950s, Crawford Hill was operating as an annex to the Holmdel laboratories and was also being used for antenna research. In the summer of 1959, the ground was cleared at the top of Crawford Hill and construction began on the Project Echo ground station.[53]

Both of the ground stations used separate antennas for transmitting and receiving. Goldstone sent west-to-east transmissions with an 85 foot diameter dish antenna that JPL specifically built for Project Echo. Signals were received at Holmdel by a 20×20 foot aperture horn-reflector antenna. Holmdel sent east-to-west transmissions using a 59 foot diameter parabolic antenna located on the same hilltop as its horn antenna. Signals were received at Goldstone using an existing antenna that had been constructed for the Pioneer program. Westbound communications used a transmission frequency of 960.05 MHz because the Goldstone receiver was already tuned to this frequency from its use in the Pioneer program.[54]

Project Echo ultimately involved transmissions from JPL's Goldstone facilities in California, the Goddard Space Flight Center in Washington, DC, the NRL facilities in Stump Neck, Maryland, and Bell Laboratories in Holmdel, New Jersey (see Fig. 17).

Satellite acquisition and tracking were accomplished using optical, digital slave, and automatic radar. Optical tracking, the simplest method, could only be used at night while the sun was illuminating the satellite so it could be seen with telescopes and television cameras at each ground station site. Camera images were displayed to a servo operator who controlled the position of the antenna to track the satellite. A separate computer system called a digital slave could acquire and track Echo 1 by receiving primary tracking data from NASA's Minitrack network of stations. The computer issued commands to control and point the antenna. The third tracking system relied on a continuous-wave radar subsystem. Although radar was not suitable for acquiring the satellite, once it had been acquired by optical or digital slave methods, radar signals could be used to automatically maintain tracking.[55]

The Holmdel Ground Station

Most of the Bell Laboratories facilities for Project Echo resided on Crawford Hill in Holmdel. This location had sufficient elevation to construct antennas for research. The facilities included a 60 foot dish that provided satellite transmitting at 960 MHz, a building

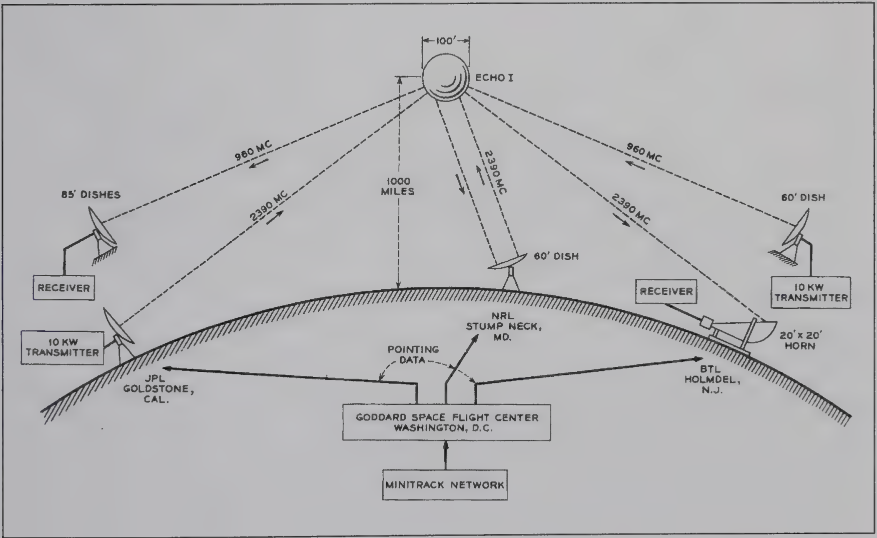


Fig. 17. Project Echo main locations. (Courtesy Bell Laboratories)

housing the transmitter controls for the dish, a building housing system controls and signal converters, the horn drive and helium equipment building to support the maser, a building for data storage, an office trailer, plus the horn antenna (see Fig. 18, Fig. 19, and Fig. 20).[56]

The system depended on an amplification concept that would eventually be used to develop laser technology, called the maser. Charles H. Townes, James P. Gordon, and Herbert J. Zeiger at Columbia University devised the first maser, achieving microwave amplification by stimulated emission of radiation. The maser generates electromagnetic waves at microwave frequencies through amplification using the process of stimulated emission whereby atoms amplify radiation after being induced into an excited state. These excitations were achieved at extremely low temperatures of approximately 2 Kelvin in liquid helium.[57]

Reception of the weak satellite signal using a large horn depended upon a maser placed at the apex of the horn. The horn focused the circularity of the weak carrier signals into the waveguide

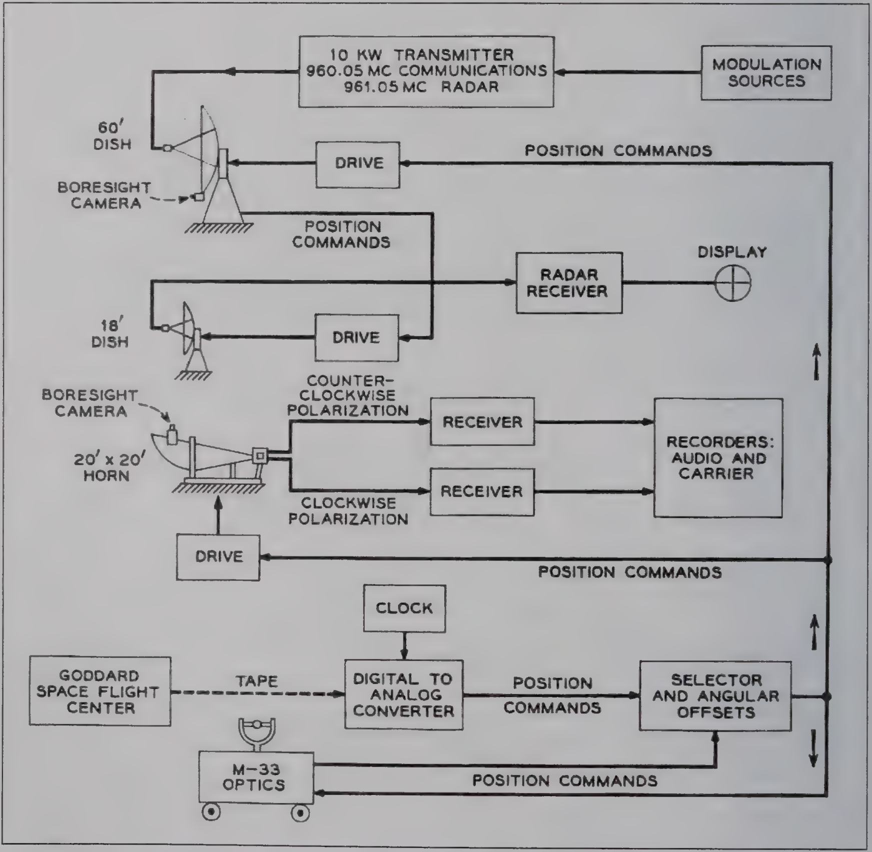


Fig. 18. Block diagram of the Holmdel facilities used in Project Echo. (Courtesy Bell Laboratories)

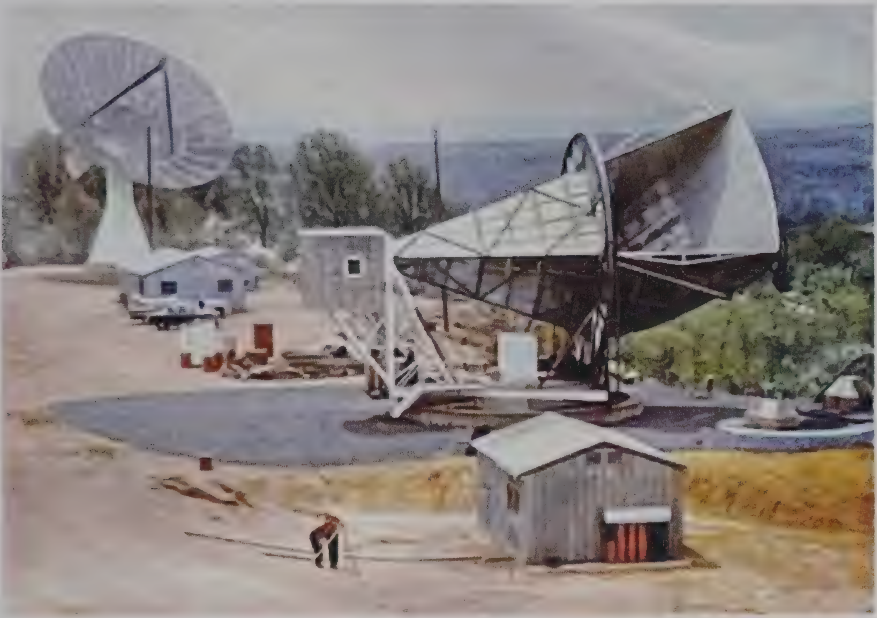


Fig. 19. The Holmdel antennas used in Project Echo. (Courtesy Bell Laboratories)

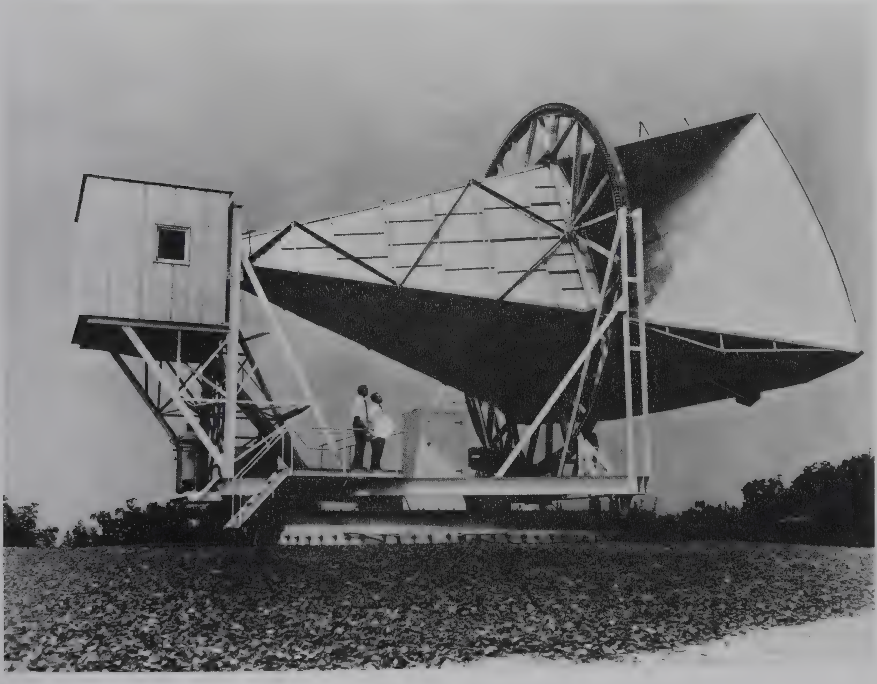


Fig. 20. The Holmdel horn antenna, circa 1961. (Courtesy Bell Laboratories)

assembly, which converted and then separated the waveguide channels. The two channels were preamplified using the maser. The signals were then heterodyned to an intermediate frequency (IF), further amplified in the IF network, and transmitted to the "output end" of the receiver (see Fig. 21 and Fig. 22).[58]

A horn antenna design offered promising returns for the satellite work in Project Echo. This type of antenna is called a Hogg or horn-reflector antenna. Albert Beck and Harald Friis came up with the basic concept by 1941.[59] R. W. DeGrasse, D. C. Hogg, E. A. Ohm, and H.E.D. Scovil developed the first horn-reflector-traveling-wave maser system by 1959.[60] A. B. Crawford, D. C. Hogg and L. E. Hunt at Bell Telephone Laboratories further developed those ideas in 1961.[61] The horn antenna consists of a flaring metal horn with a metal reflector mounted in the mouth at a 45° angle. The structure was made of aluminum. The elevation wheel was 30 feet in diameter, and it rotated with wheels on a track that was 30 feet in diameter. The sides of the horn were flat surfaces, and the front and back surfaces were conic sections. This design had advantages over a parabolic dish antenna. Since it has very low sidelobes, the horn shields the antenna from radiation present from angles outside the main beam axis, such as ground noise.[62]

Given the low noise properties of horn speakers, researchers at the Bell Laboratories Holmdel Radio Research

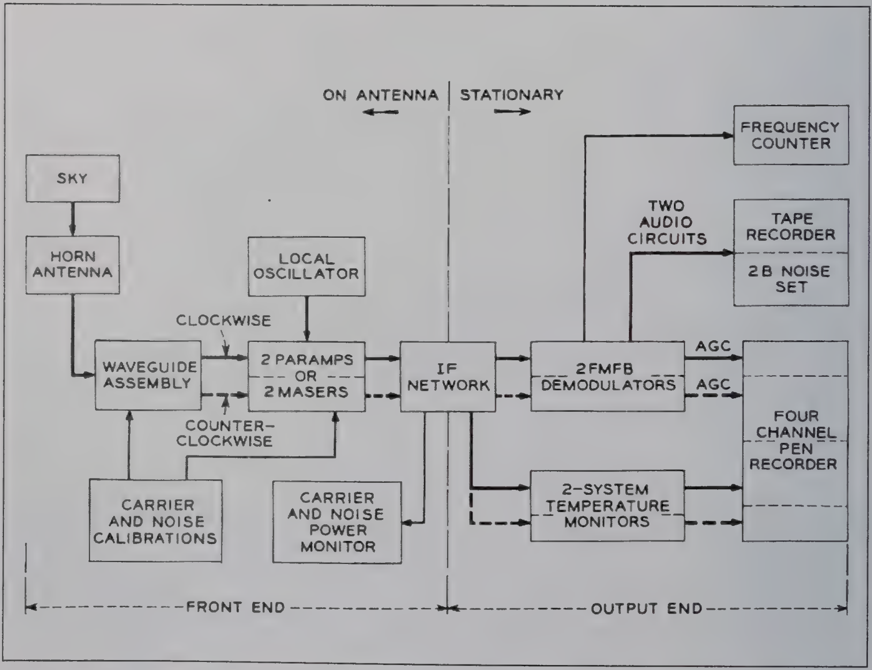


Fig. 21. Block diagram of the Holmdel horn receiver. (Courtesy Bell Laboratories)

Laboratory constructed their giant horn-reflector antenna with 400 square feet of effective aperture. This type of horn-reflector did not detect extraneous ground noise, even when pointed only a few degrees above the horizon. In addition to its broadband characteristics, the antenna was designed so the receiving equipment did not move with the elevation motions of the horn. These advantages would prove important and would be replicated on a much larger scale in Andover for the Telstar satellite experiments (see Fig. 23).[63]

The Holmdel Horn Antenna was "extremely broad band, has calculable aperture efficiency, and the back and side lobes are so minimal that scarcely any thermal energy is picked up from the ground."[64] It was considered an ideal radio telescope for accurate reception of Telstar signals and would later be used to measure low levels of weak, cosmic background radiation. A plastic clapboarded utility shed with dimensions of 10 x 20 feet with two windows and a double door stood next to the horn antenna, housing equipment and controls for the antenna. When not in use, the antenna azimuth sprocket drive could be disengaged, permitting the structure to experience minimum wind resistance. The antenna was designed to withstand winds of 100 miles per hour and the entire structure weighed 18 tons.[65] A transmission frequency of 2390 MHz was ultimately selected, as this was the planned frequency band for future satellite experiments.

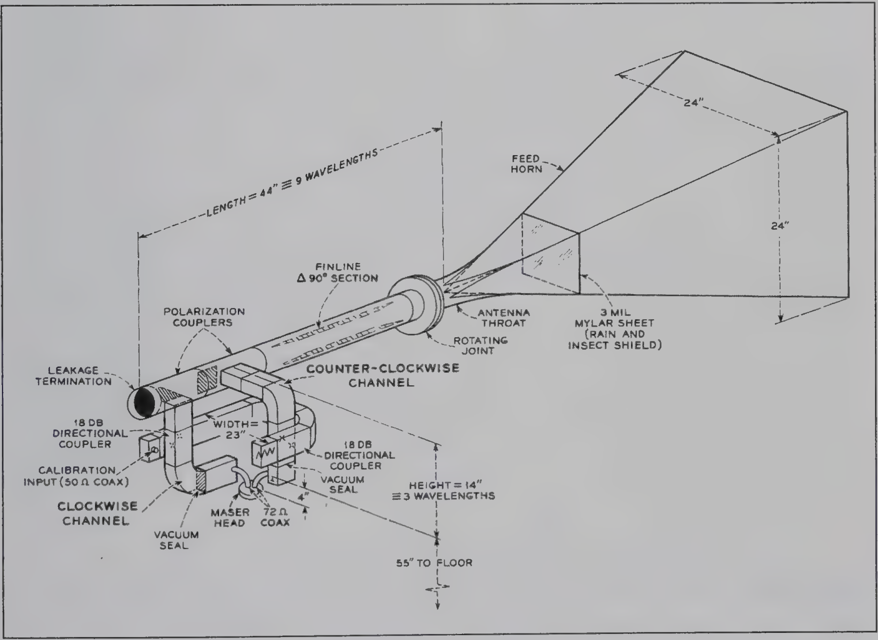
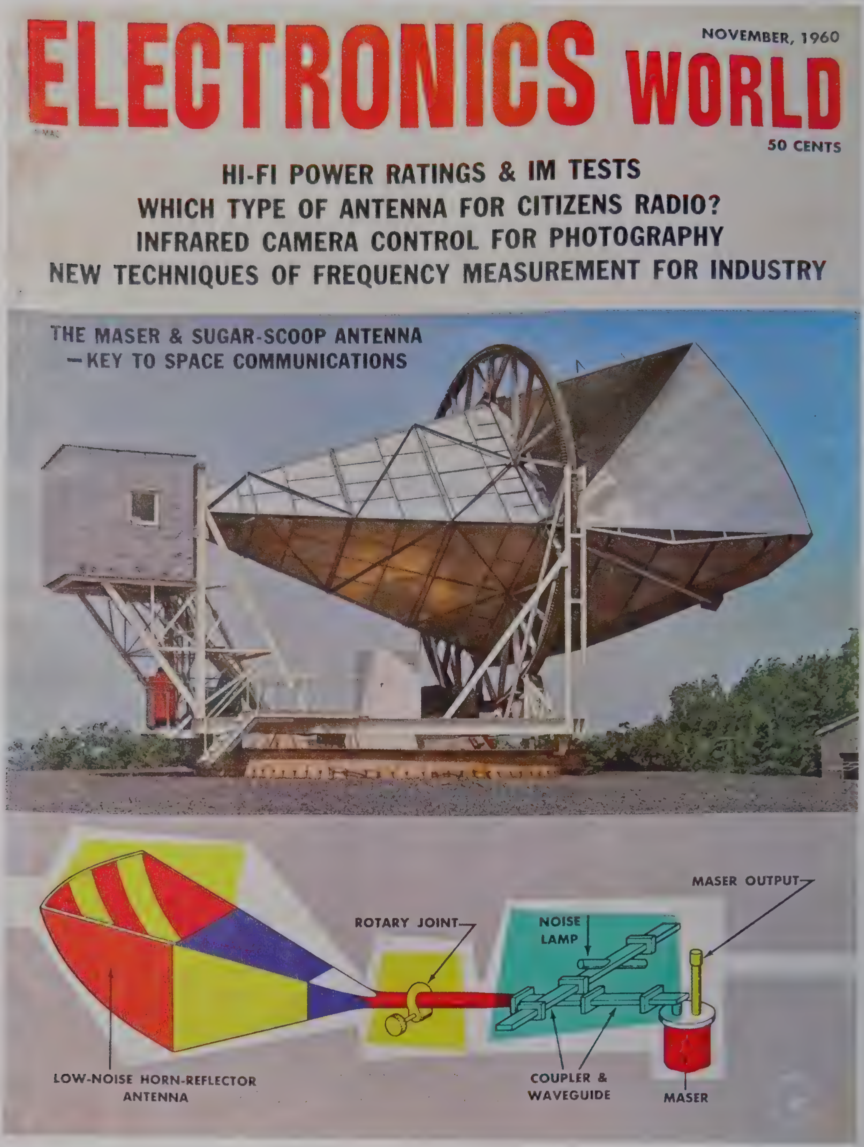

24"
FEED HORN
24"
LENGTH = 44" ≡ 9 WAVELENGTHS
FINLINE Δ 90° SECTION
POLARIZATION COUPLERS
ANTENNA THROAT
3 MIL MYLAR SHEET (RAIN AND INSECT SHIELD)
ROTATING JOINT
COUNTER-CLOCKWISE CHANNEL
LEAKAGE TERMINATION
18 DB DIRECTIONAL COUPLER
WIDTH = 23"
18 DB DIRECTIONAL COUPLER
CALIBRATION INPUT (50 Ω COAX)
VACUUM SEAL
HEIGHT = 14" ≡ 3 WAVELENGTHS
4"
CLOCKWISE CHANNEL
MASER HEAD
72 Ω COAX
VACUUM SEAL
55" TO FLOOR

Fig. 22. Schematic diagram of the Holmdel horn antenna waveguide assembly that connected to the maser head. (Courtesy Bell Laboratories)



ELECTRONICS WORLD

NOVEMBER, 1960

50 CENTS

HI-FI POWER RATINGS & IM TESTS

WHICH TYPE OF ANTENNA FOR CITIZENS RADIO?

INFRARED CAMERA CONTROL FOR PHOTOGRAPHY

NEW TECHNIQUES OF FREQUENCY MEASUREMENT FOR INDUSTRY

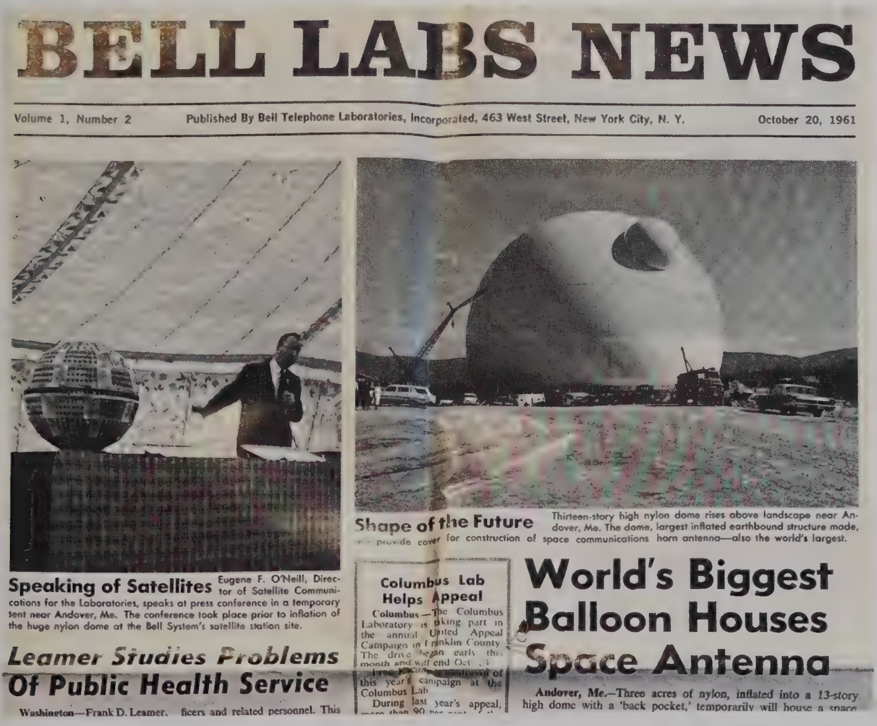
THE MASER & SUGAR-SCOOP ANTENNA
—KEY TO SPACE COMMUNICATIONS

Fig. 23. Cover of *Electronics World*, Nov. 1960, featuring the Holmdel horn antenna and showing the location of the maser.

The Andover Ground Station

Based on results from Project Echo, AT&T and Bell Laboratories built the Andover Horn Antenna. Construction took place in 1961. The 1000-acre tract for the site was selected in December 1960 based on the remote topography in the mountains of western Maine and the low radio interference signal levels. Other factors included a location in the northeastern United States which gave a short great circle path to western Europe. It was also located close enough to existing transcontinental radio relay television and telephone routes to facilitate interconnection. In addition, the site could accommodate an antenna structure and control building for a much larger version of the Holmdel horn design and still provide room for future expansion and the addition of other facilities. Plans contemplated erecting five antennas to provide three broadband channels, with one antenna always available for handover and another available as a spare. The antennas were situated to prevent overlapping their microwave signals at elevations above 7.5 degrees.[66]

The land was purchased in January 1961, and construction began on May 1. Soon, the area was dubbed "Space Hill."[67] AT&T and Bell Laboratories publicized the progress of construction and the development of Telstar, keeping the public informed while also promoting the project (see Fig. 24). Construction of the buildings was finished, and the equipment was installed in February 1962 (see Fig. 25). The Andover Ground Station went operational by the spring



BELL LABS NEWS

Volume 1, Number 2 Published By Bell Telephone Laboratories, Incorporated, 463 West Street, New York City, N. Y. October 20, 1961

Speaking of Satellites Eugene F. O'Neill, Director of Satellite Communications for the Laboratories, speaks at press conference in a temporary tent near Andover, Me. The conference took place prior to inflation of the huge nylon dome at the Bell System's satellite station site.

Shape of the Future Thirteen-story high nylon dome rises above landscape near Andover, Me. The dome, largest inflated earthbound structure made, [illegible] provide cover for construction of space communications horn antenna—also the world's largest.

Leamer Studies Problems Of Public Health Service

Washington—Frank D. Leamer, ficers and related personnel. This

Columbus Lab Helps Appeal

Columbus—The Columbus Laboratory is taking part in the annual United Appeal Campaign in Franklin County. The drive began early this month and will end Oct [illegible] of this year's campaign at the Columbus Lab

During last year's appeal,

World's Biggest Balloon Houses Space Antenna

Andover, Me.—Three acres of nylon, inflated into a 13-story high dome with a 'back pocket,' temporarily will house a space

Fig. 24. *Bell Labs News*, Oct. 20, 1961, with a press conference from Eugene O'Neill, Telstar project director at Andover, describing the progress in building the radome and constructing the Telstar satellite. (Authors' collection)

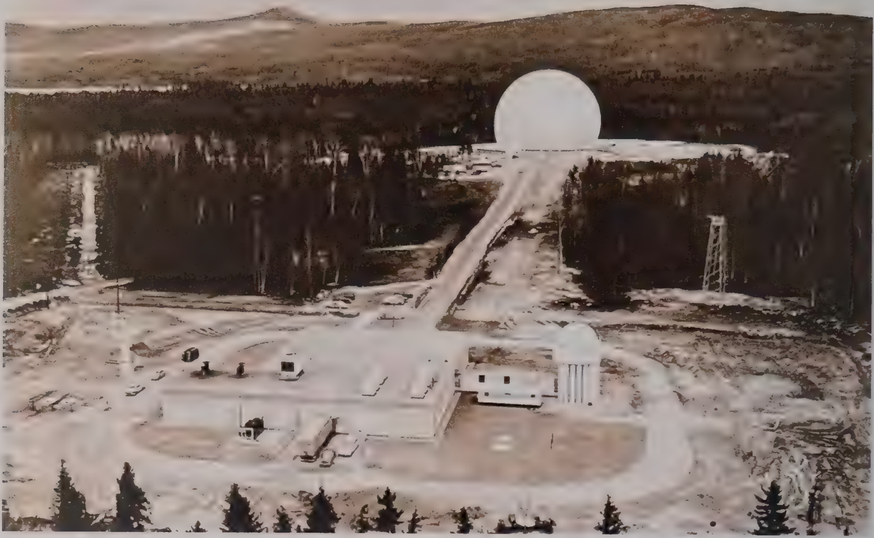


Fig. 25. Andover Earth Station circa 1961 with the control building in the foreground and the radome approximately a quarter mile in the background, with the helical antenna on the left and the tracking antenna on the right of the control building. (Authors' collection)

Fig. 26. Some of the 500 international news correspondents and their spouses who visited Andover Earth Station courtesy of the Rotary Club, Aug. 1962. (Authors' collection)

of 1962, all under the direction and with funding provided by AT&T and Bell Laboratories.[68] The state of Maine, local clubs, AT&T, and Bell Laboratories wasted no time in providing numerous tours and bringing the international press corps to see the remote new facility (see Fig. 26).

The Great Andover Horn Antenna

The centerpiece of the Andover Earth Station was the immense horn antenna within the radome. The McKiernan-Terry Corporation of Dover and Harrison, New Jersey, were the prime contractors who followed Bell Laboratories' and AT&T's basic designs for the antenna.[69] Bell Laboratories and AT&T considered six possible concepts. The final design included the broadest range of system and design features compared to the other alternatives (see Fig. 27 and Fig. 28).[70]

The Andover structure was anchored into bedrock 15 feet below grade and was capable of "a horizontal reaction of 300,000 pounds which could develop if, in the event of a hurricane, the protective radome were lost and the structure were subjected directly to the full force of a 100 mph wind."[71] The outer azimuth rotation track was 136 feet in diameter, made up of 24 segments of heavy-duty crane rail weighing 171 pounds per yard. The inner track was 74 feet in diameter, containing twelve tracks of the same rail (see Fig. 29).[72]

The elevation structure was formed by an extremely rigid framework, which housed a conical horn that was approximately 90 feet long and supports a reflecting surface measuring

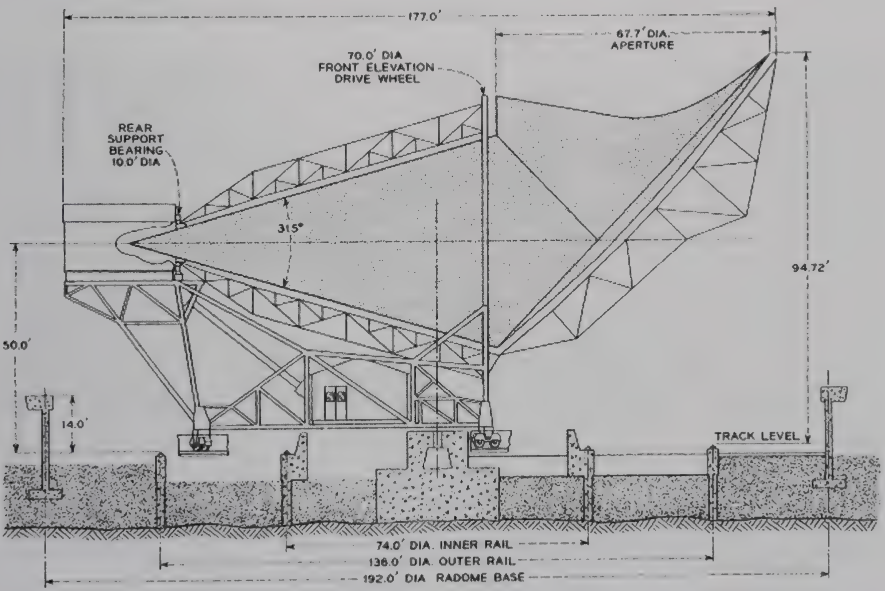


Fig. 27. Schematic diagram of the Andover horn-reflector antenna. (Courtesy Bell Laboratories)

approximately 100 by 70 feet. The horn terminated at its apex in an enclosed room housing the transmitting and low-noise receiving equipment. The mouth of the horn at its large end was a reflector in the shape of a paraboloid of revolution set at an angle of 45 degrees to the axis of the cone. The space between the horn and reflector was occupied by a cylindrical structure that served as a shield for the 68 foot diameter aperture of the antenna. "The entire antenna structure is 177 feet long, stands some 95 feet above the azimuth rails at maximum elevation angle, and weighs about 380 tons with all equipment installed"[73] (see Fig. 30).

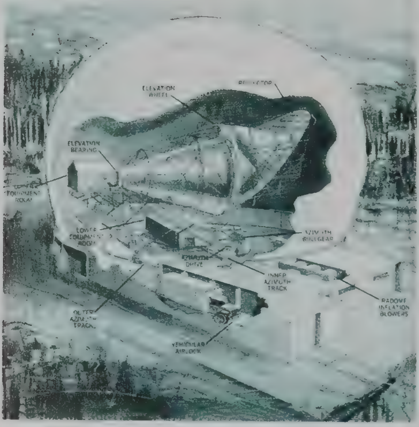


Fig. 28. Artist's rendering for the Andover horn antenna in the inflated radome. (Courtesy Bell Laboratories)

The cone, shield, and reflector surfaces were made of aluminum honeycomb panels, each averaging 3 by 12 feet in area and weighing about one pound per square foot. These panels included two 0.020 inch sheets of aluminum separated by a 1 to 1½ inch thick lightweight aluminum honeycomb core. This design maximized rigidity, minimized weight, and provided shielding to block stray radio frequency interference (see Fig. 31).[74]

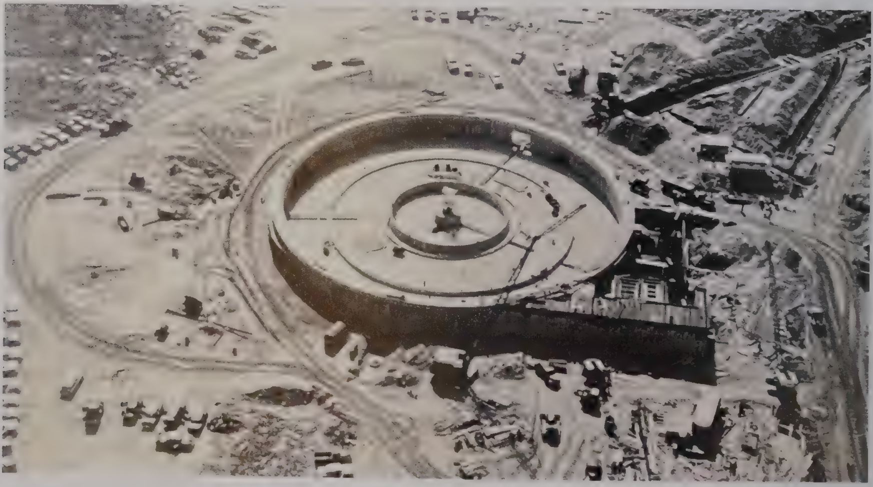


Fig. 29. Construction of the Andover horn antenna showing the 200 foot diameter and 16 feet high foundation for the 380 ton horn antenna and radome. The inner rings for the antenna track are visible. (Courtesy Bell Laboratories)

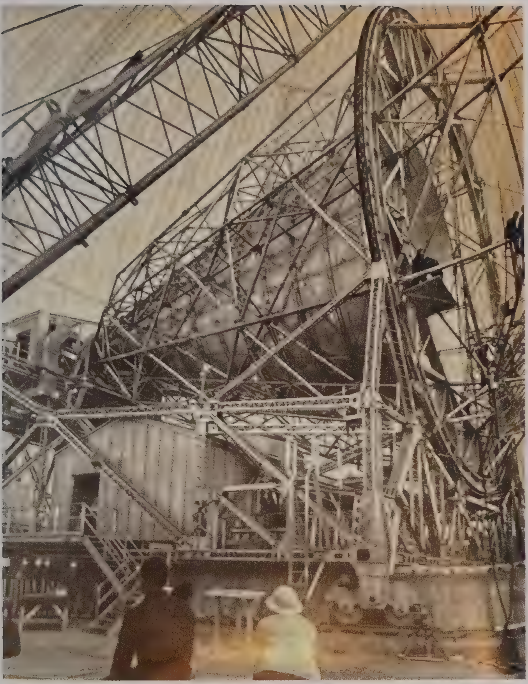


Fig. 30. Construction of the Andover horn antenna showing the 70 foot rotating elevation drive ring gear on the right. (Courtesy Bell Laboratories)

Just as at Holmdel, the main signal amplifier at Andover was a maser, although the Andover antenna employed the more advanced type of "ruby" maser. The horn funneled from its 68 foot wide mouth down to a one square inch waveguide and into a pencil-thin tube leading to the ruby maser (see Fig. 32). The maser's extremely low noise amplifier with a central element made of a ruby rod immersed in liquid helium at negative 456 °F (2 Kelvin), made it capable of boosting the one-billionth of a watt signal picked up by the horn to a usable strength.[75]

Protection of the antenna with a radome was essential. Bell Laboratories' research concluded that:

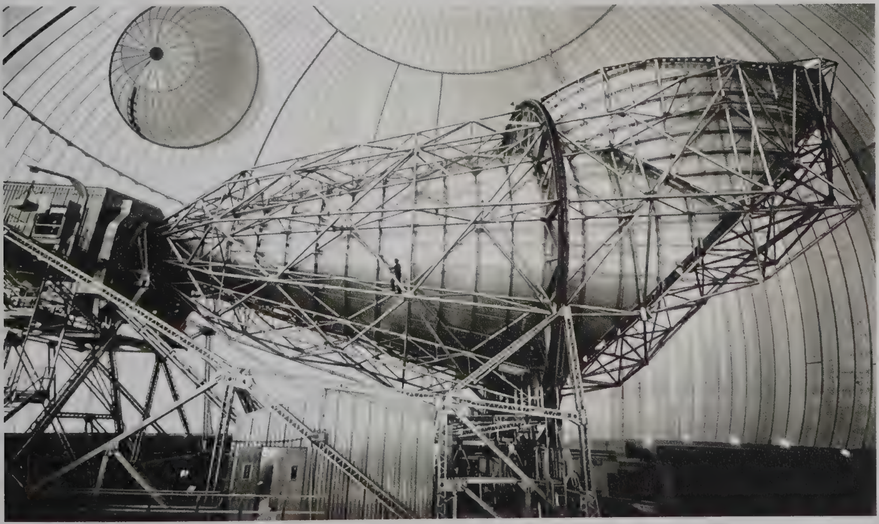


Fig. 31. The great horn antenna at Andover. Note the small black figure in the center of the image, which is a person standing in the framework. (Courtesy Bell Laboratories)

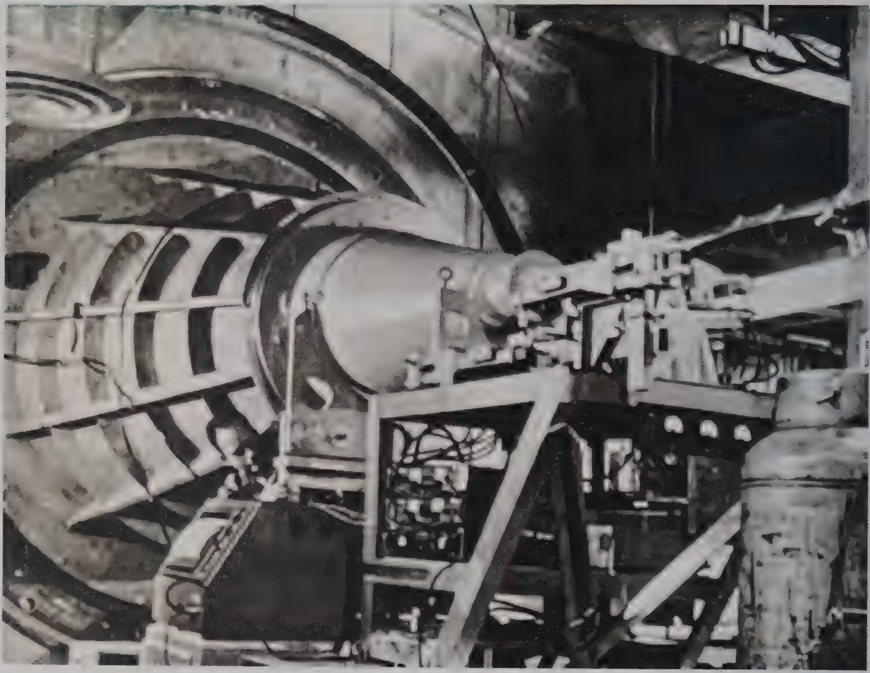


Fig. 32. The autotrack microwave frequency unit at the apex of the Andover horn antenna. A person is visible on the lower left, showing the size of the horn's apex. (Courtesy Bell Laboratories)

> "[w]ithout radome coverage, the antenna would be subject to the effects of the common elemental conditions of the area, such as solar heat, wind, snow, ice, rain, and dust…disturb[ing] the antenna reflecting surface contour accuracy so that the required patterns and gain are not achieved. Furthermore, differential solar thermal distortion can adversely affect beam pointing accuracy."[76]

Aside from structural concerns of building such a large radome, one capable of withstanding 100 mph winds and weather extremes, the pressure exerted inside the inflatable dome of 28 psi raised new concerns focused on signal interference (see Fig. 33). Any protective coating for the base material had to be tough, durable, and resistant to both abrasion and erosion from weathering and ultraviolet exposure. It also needed to have a relative dielectric constant as low as possible (3.0 in the case of the Telstar system) and a thickness of no more than 0.071 inch and must be held to an overall thickness tolerance of +/- 0.002 inch.[77] No off-the-shelf options were available for the fabric.

A special radome skin was fabricated from a yarn made of Dacron polyester fiber, hot-stretched and heat-stabilized. The radome fabric was specially woven to the heaviest gauge within loom capacity, coated, and two such fabric layers were

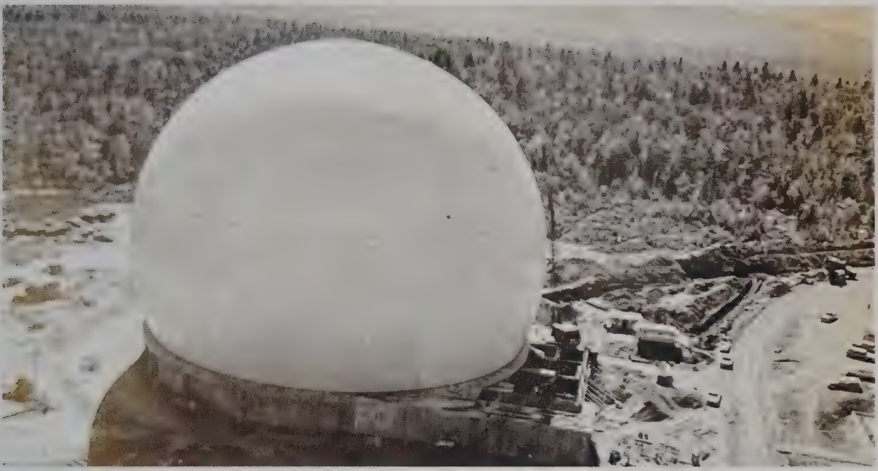
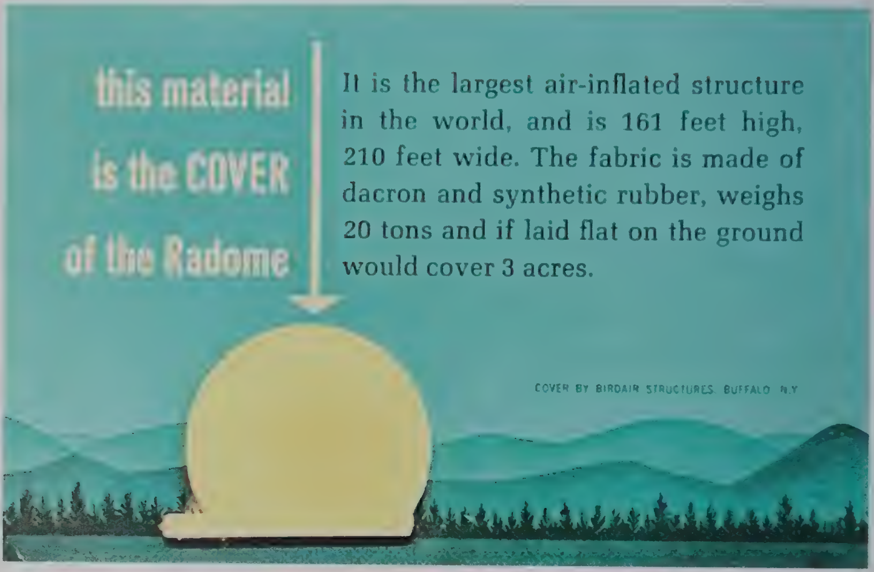


Fig. 33. Construction of the Andover radome, 161 feet high and 210 feet in diameter. (Courtesy Bell Laboratories)

laminated together in a herringbone pattern. The coating material was a synthetic rubber based on Hypalon, a DuPont proprietary material, that was specially formulated to minimize RF loss and moisture permeability. Commercially available Hypalon air-curing cements further developed the strengths of the inter-laminar and joint-bonds. Birdair Structures, Inc. of Buffalo fabricated the structure.[78] B. F. Goodrich sealed more than 7 miles of seams between sections on the radome with its own invention, Radalon, a flexible non-cracking paint.[79] Samples of the radome fabric can still be found on postcards issued by Bell Laboratories (see Fig. 34).

Bell Laboratories published complete specifications of the horn antenna designs in its journals and through NASA. The final network included the great horn antenna at Andover, Maine; AT&T data systems in New York; AT&T telephone systems in White Plains, New York; and the original horn antenna in Holmdel, New Jersey. Andover maintained 48 telephone lines and trunks for voice frequency, data, and telephone circuit order wire connections. Ten other locations were involved with the Telstar signals, all tied together through the control buildings that also housed the tracking systems and computer. Further, the Andover control buildings had teletypewriter connections with eight other locations involved with the Telstar signals (see Fig. 35).[80]

Telstar's radio transmitter was very low-powered at only 14 watts, and it transmitted through an omnidirectional antenna. Consequently, the Andover ground antennas needed to compensate, and they were huge. The giant horn antenna was seven stories high and weighed 380 tons.[81] The radome was 160 feet high, 210 feet wide, and weighed 30 tons. Since Telstar passed overhead quickly in its orbit, the giant horn antenna had to be capable of tracking the satellite as it moved across the sky. This required precision steering mechanisms and significant power to run the machinery and the communication systems. Approximately 1,000 kW



this material
is the COVER
of the Radome

It is the largest air-inflated structure in the world, and is 161 feet high, 210 feet wide. The fabric is made of dacron and synthetic rubber, weighs 20 tons and if laid flat on the ground would cover 3 acres.

COVER BY BIRDAIR STRUCTURES BUFFALO N.Y.

Fig. 34. Postcard with a sample of fabric from the radome by Birdair Structures, Inc. (Authors' collection)

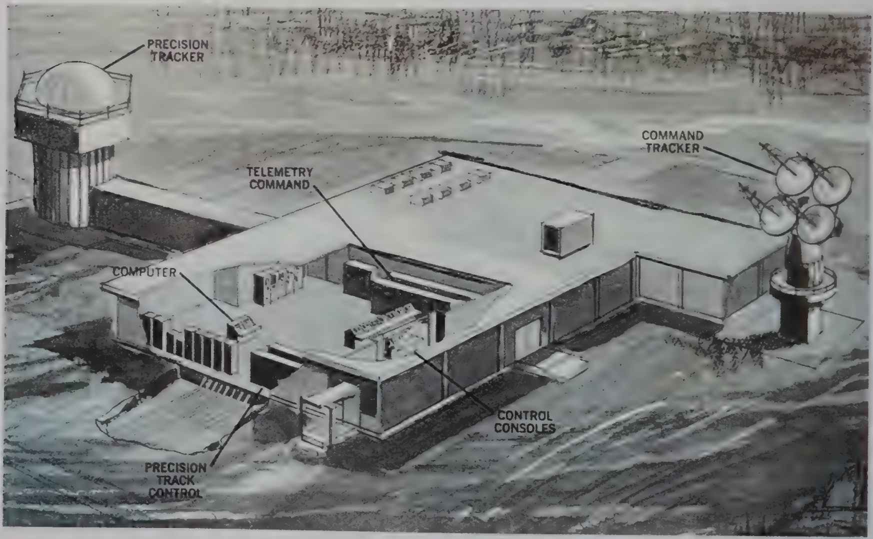


Fig. 35. Control buildings at Andover Earth Station. (Courtesy Bell Laboratories)

of 60 cycle alternating current energized the rectifiers in the technical equipment and other loads such as motors, lights, and other utilities. Two sources supplied current: (i) commercial service from the local public utility company, and (ii) a self-contained prime power plant equipped with diesel engine-generator sets.[82]

Thus, the Andover horn antenna was a significantly larger version of the one in Holmdel (see Table 4). Although

Table 4. Comparison of Holmdel and Andover horn antenna characteristics. (Source: NASA Compendium of Satellite Communications Programs (Computer Sciences Corporation for NASA, Contract Nos. NAS 5-24011 and NAS 5-24012, Dec. 1975), pp. 3–14, 6–9.)

Comparison of Horn Antenna Characteristics

	Holmdel	Holmdel	Andover
SATELLITE PROGRAM			
Satellite	**Echo**	**Telstar**	**Telstar**
Role	Receive	Receive	Receive, Transmit
ANTENNA			
Horn Type (All Reflectors)	Pyramidal	Pyramidal	Conical
Mouth Type	Square	Square	Circular
Aperture Diameter (feet)	20 x 20	20 x 20	68
Length (feet)	50	50	177
Receive Gain (dB)	43	48	58
Efficiency (%)	72	70–75	70–75
Receive Beamwidth (deg @ 3dB Pts.)	1.2	0.78	0.23
RECEIVING SYSTEM			
Preamplifier	Maser	Maser	TWT Ruby Maser
Bandwidth (MHz)	2 @ 3 dB Pts	20 @ 1 dB Pts	25 @ 3 dB Pts
Noise (K at degrees elevation)	45 @ 7.5 degrees	17 @ 90 degrees	32 @ 90 degrees
TRANSMISSION SYSTEM			
Amplifier	None	None	TWT
Bandwidth (MHz)			32 @ 1 dB Pts
Amp. Power Output (kW)			2
TRACKING			
Type	Program Track, Optical Track, Mannual Control Radar Track	Predicted Look Angles plus Manual Correction of Errors Detected on Separate 18 ft. Dish Tracker	Autotrack by Command Tracker, Precision Tracker, or Vernier Tracker by separate antenna
Accuracy (degrees)	Program +/- 0.2, Optical +/- 0.05, Radar +/- 0.1	+/- 0.05	+/-0.01, Vernier +/-0.005
PERFORMANCE			
Gain-to-Noise, G/T (dB/K)	26.5	36	40.7
Effective Isotropic Radiated Power, EIRP (dBm)	None	None	123

the Andover site was built to transmit and receive signals from Telstar, Bell Laboratories also modified and expanded the Holmdel site for it to receive Telstar transmissions. Since Andover remained the central control point for Telstar, Holmdel's signal reception from Telstar was forwarded to Andover via telephone network lines.[83] The Andover horn antenna was attached to a control building housing a precision tracker, beacon tracker, and a microwave link that was connected to AT&T's national microwave network. The Andover horn antenna was highly precise; with a pointing accuracy of one minute of arc as it rotated on two flat tracks that were able to move the antenna within 30 thousandths of an inch precision (Table 5).[84]

The designs for the Andover Earth Station were replicated in Europe. A similar ground station was built in France with a very similar horn antenna and radome. Other tracking stations were also constructed, using conventional radio telescopes but both the British and French stations employed 2 kW TWTs in their systems.[85]

Acquisition, Tracking, and Success

The final tracking system for Telstar involved antenna control equipment, precision tracker control, and command tracker control—all coordinated through autotrack and slave circuits tied to the great Andover horn antenna. The autotrack system microwave frequency unit was located in the base of the horn, enabling the main antenna to be kept on target from the 4.08 GHz beacon after initial acquisition was made on the 136 MHz transmitting beacon. The narrow beam precision tracker and horn reflector then tracked the 4.08 GHz microwave beacon switched on by the command tracker (see Fig. 36). This overall concept used principles developed from radar applications and relied on Bell Laboratories' significant experience in developing guided missile systems, computers, and microwave communications.[86]

The orbital tracks for Telstar meant it was only in view of the tracking stations in the United States and Europe for the periods where it was over the eastern United States and the Atlantic Ocean

Table 5. Overall system parameters at Andover, circa 1962. (Source: Bell Laboratories Record, Special Telstar Issue, Apr. 1963, p. 136.)

Overall System Parameters at Andover			
Transmitter		**Receiver**	
Frequency (MHz)	6390	Frequency (MHz)	4170
Output Power Range (W)	0.2 to 2000	Input Signal Range (dBm)	-70 to -100
RF Bandwidth (MHz)	>32	Noise Temperature (K)	32
Peak Deviation (MHz)	10	Overall Bandwidth (MHz)	25
Deviation Sensitivity	20 MHz/v	--	--
Baseband Width	2 Hz–5 MHz	Baseband Width	2 Hz–3 MHz
Input Imped. (ohms balanced)	124	Output Imped. (ohms balanced)	124

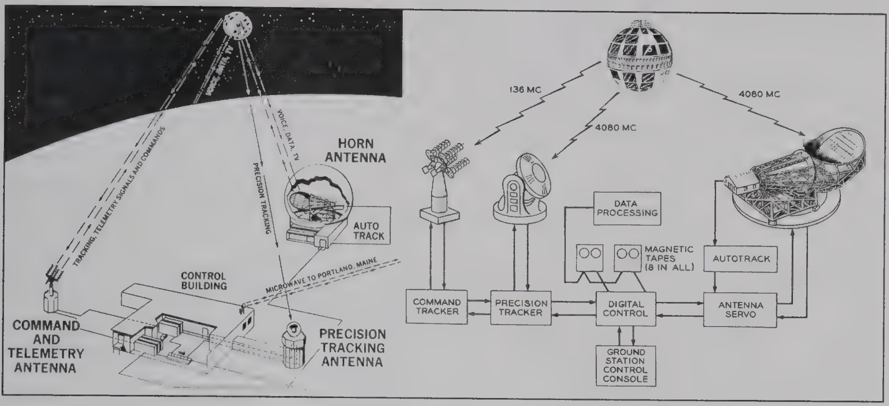


Fig. 36. Two schematic diagrams showing the physical and functional relationships of the Telstar acquisition and tracking system. (Courtesy Bell Laboratories)

(see Fig. 37). In July 1962, everything was ready.

The press, and in turn the public, was kept well informed by AT&T and Bell Laboratories that provided substantial background information for publication through the international press. Telstar launched on July 10, 1962, from Cape Canaveral Air Force Station and went into orbit at 4:46 a.m. (see Fig. 38). The engineers at Andover Earth Station waited 15 hours for the satellite, traveling at a rate of 5 miles per second at an altitude of 3,000 miles above the Earth,

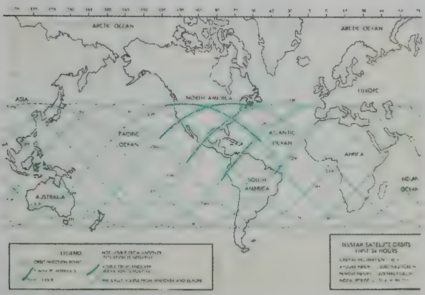


Fig. 37. The suborbital tracks for Telstar 1 in the first 24 hours. The solid lines are visible from Andover. The double lines over the Atlantic Ocean are the periods of visibility for both the United States and European stations. (Courtesy Bell Laboratories)

Fig. 38. Postcard of the Telstar 1 launch on July 10, 1962, aboard a Thor-Delta rocket. (Authors' collection)

to reach their "view" in the testing area (see Fig. 39 and Fig. 40). Holmdel provided beacon tracking before the signal reception tests were performed on Telstar's first pass (see Fig. 41). Andover also tracked Telstar's visible passes (see Fig. 42). W. C. Jakes oversaw the Holmdel signal tests with R. Klain, G. J. Stiles, and L. R. Lowry as Telstar passed overhead (see Fig. 43). Finally, the engineers successfully sent a signal to Telstar, which amplified it 10 billion times, and the satellite relayed the signal back to Andover during the first transmission tests (see Fig. 44).

Eugene O'Neill, Telstar project director at Andover, announced the reception of the first signal on July 10 at 7:17 p.m. EDT stating, "We've acquired Telstar!"[87] At 7:30 p.m. EDT, F. R. Kappell, chairman of AT&T, placed a telephone call through Telstar to U.S. Vice President Lyndon Johnson. At 7:33 p.m. EDT, an American flag at Andover appeared on the television screen as television transmission commenced in the United States. At 7:47 p.m. EDT, engineers at Andover received word that the French site, Pleumeur-Bodou, had received the television picture in real time (see Fig. 45).[88]

Considerable public interest had gained worldwide attention, and millions of people around the world witnessed the subsequent live television signals, including a press conference from President Kennedy that Telstar transmitted to France. Magazines and newspapers celebrated the participation of countries and companies worldwide. *Business Week* stated that the "list of guest experimenters reads like a blue book of international commerce and industry."[89] The U.S. State Department and U.S. Information Agency contemplated the

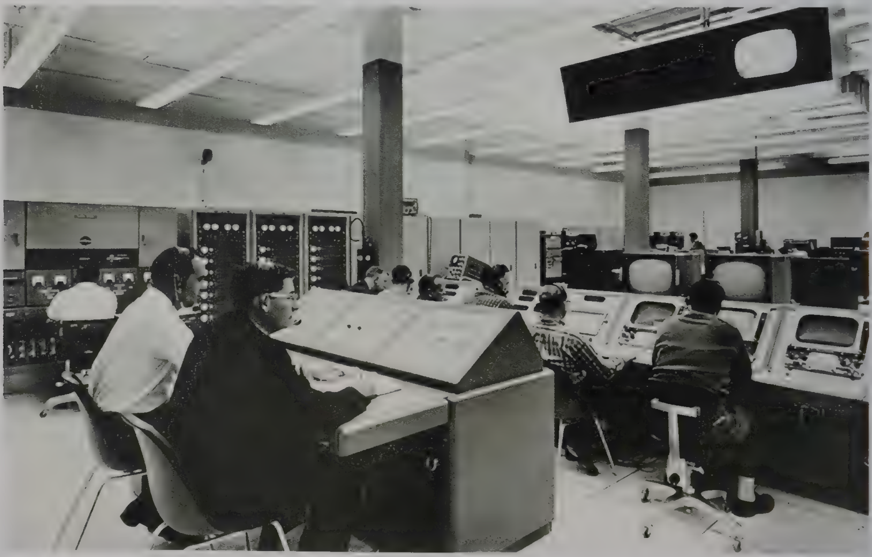


Fig. 39. Control room for Telstar 1 at Andover Earth Station. (Authors' collection)

enhanced possibilities for international cooperation and U.S. dominance, seeking to connect as many countries as possible as quickly as possible using satellite communications, even while the U.S. Defense Department explored ways to use the new technology for military applications.[90]

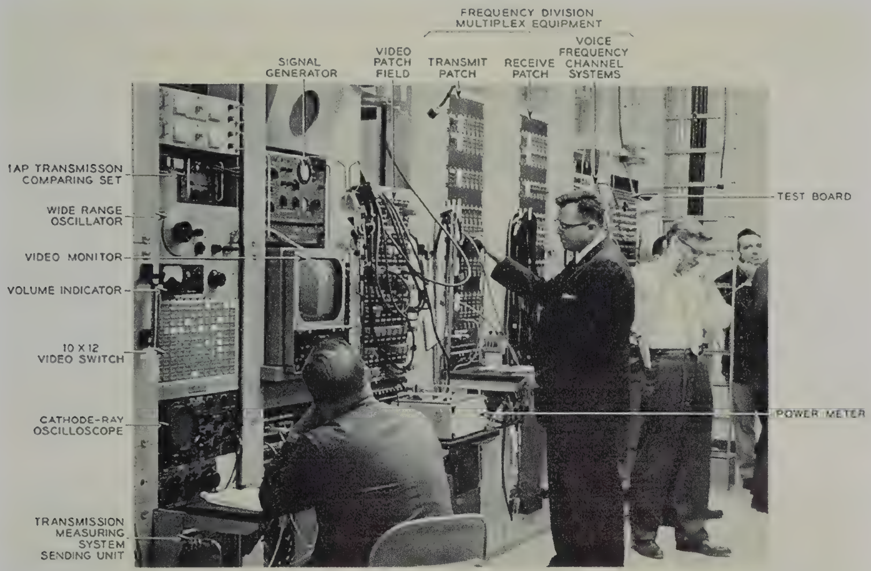


Fig. 40. Telstar 1 testing area at Andover Earth Station. (Courtesy Bell Laboratories)

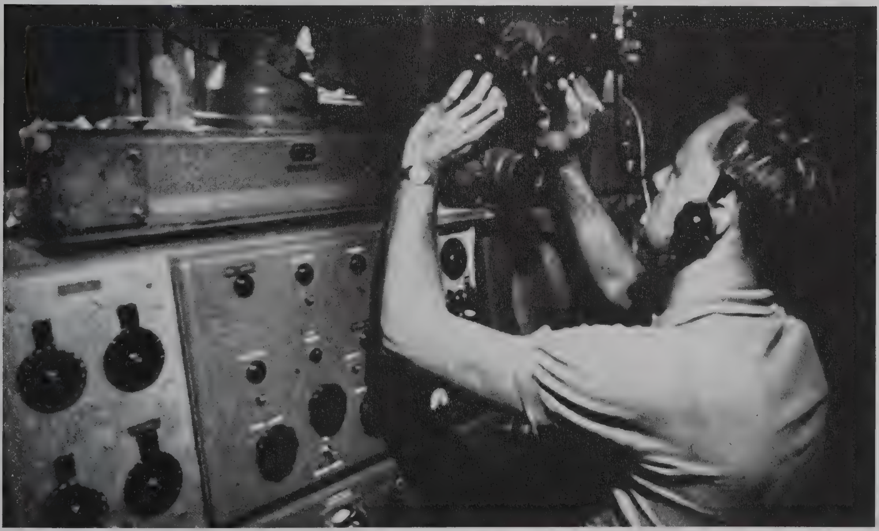


Fig. 41. Beacon tracking console at Holmdel. (Courtesy Bell Laboratories)

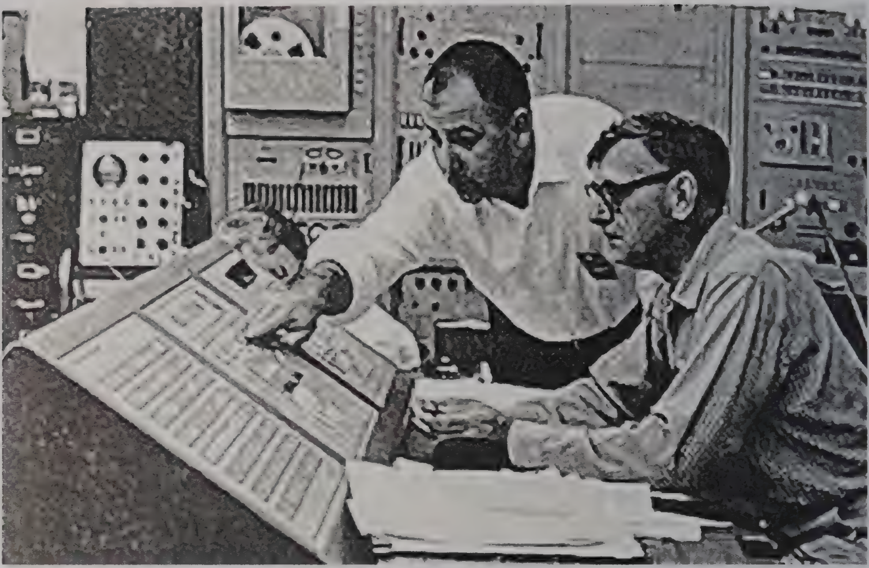


Fig. 42. Andover tracking tests during initial passes of Telstar. (Courtesy Bell Laboratories)

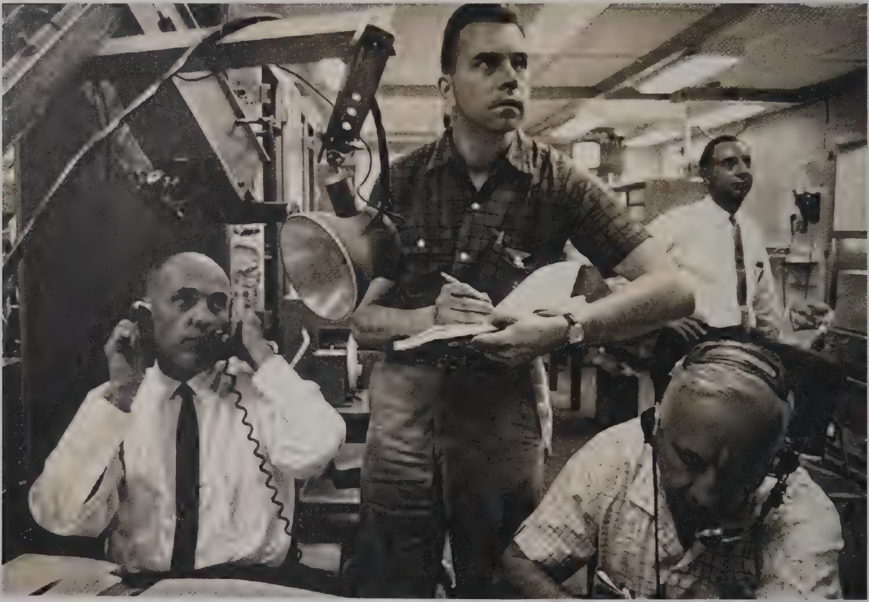


Fig. 43. W. C. Jakes (left), R. Klahn (standing center), J. Stiles (background), and L. R. Lowry (seated right) wait for Telstar's first pass to perform signal tests. (Courtesy Bell Laboratories)

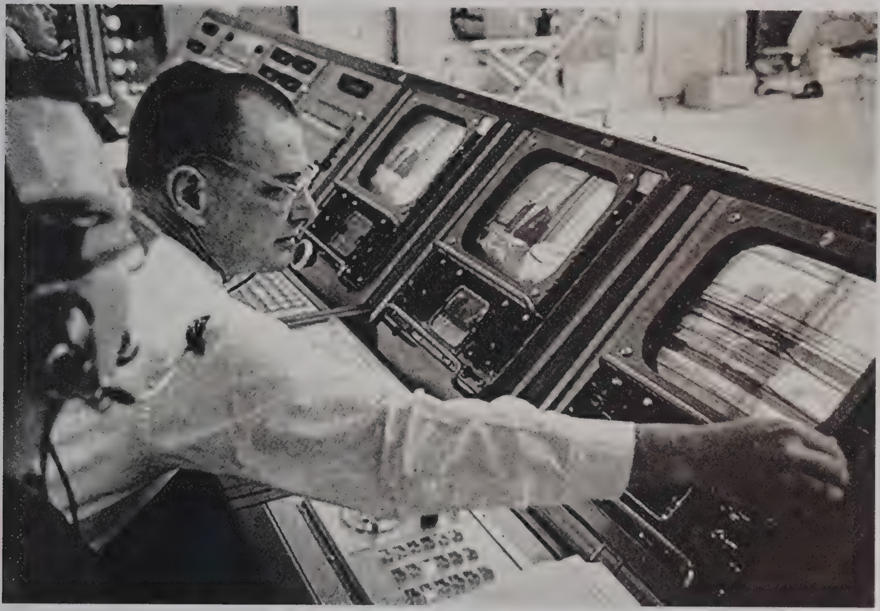


Fig. 44. Adjusting Andover control room signal levels on television monitors during Telstar's first pass. (Courtesy Bell Laboratories)

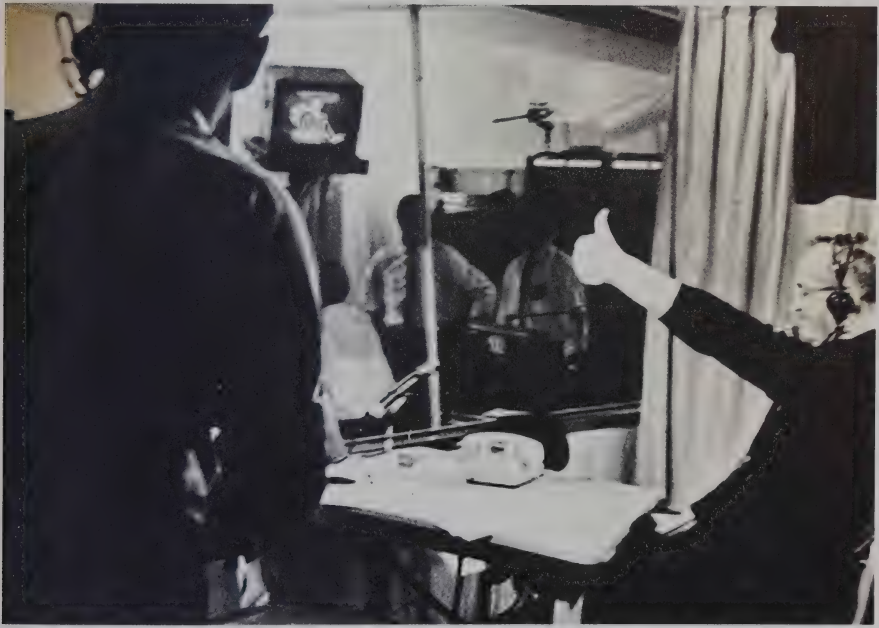


Fig. 45. Telstar project director Eugene O'Neill acknowledges that the French station has received the first television signals from Telstar. (Courtesy Bell Laboratories)

NASA benefitted from the success of Telstar as well. Its budget for communications satellites grew from \$35.5 million in 1962 to \$55.8 million in 1964. Its total satellite and applications program budget nearly doubled, growing from \$76.2 million in 1962 to \$140.7 million in 1964.[91]

The success of Telstar, following on the heels of Explorer, Vanguard, Echo, and other satellites, ignited the public's imagination for the prospects of developing space technologies. A British band named the Tornados recorded "Telstar," a hit song widely played in the United Kingdom that reached number 1 in the United States on Billboard magazine's popularity chart.[92] Sheet music for "Telstar" was also released in the United States and United Kingdom (see Fig. 46). A U.S. Information Agency poll found that in the United Kingdom, Telstar was better known in 1962 than Sputnik was in 1957.[93]

AT&T and Bell Laboratories featured Telstar as well as the Holmdel and Andover horn antennas in advertising,

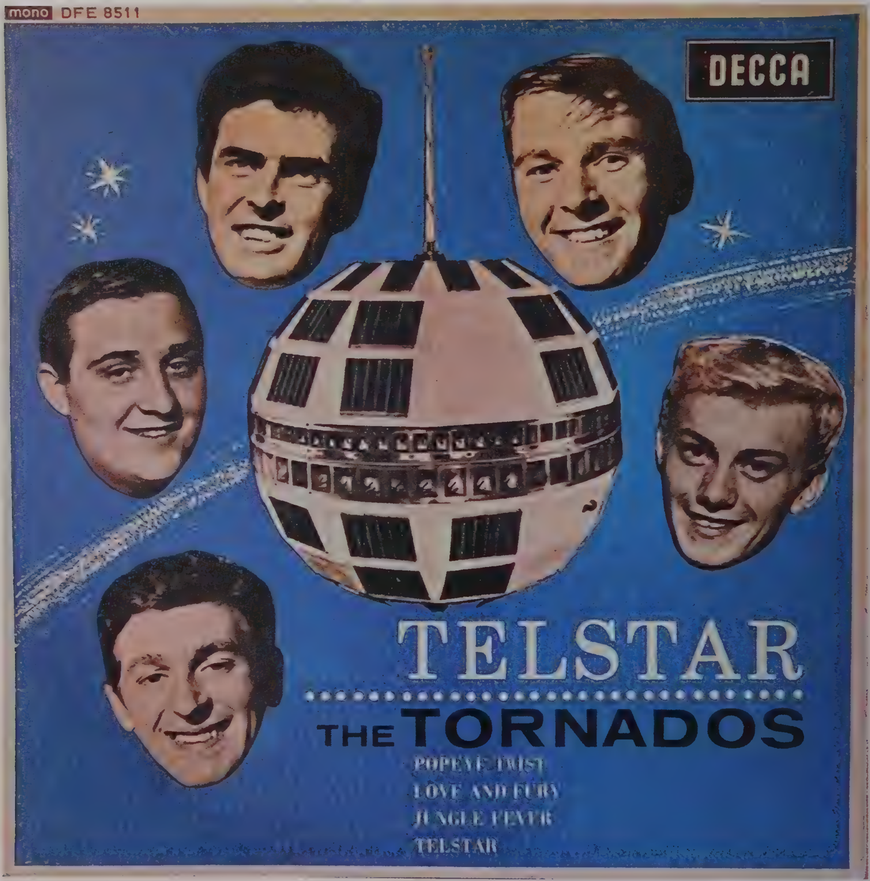


Fig. 46. 45-RPM record "Telstar" by the Tornados released by Decca Records. (Authors' collection)

educational booklets, pamphlets, jewelry, commemorative plates, glassware, and postcards. They also produced educational films about space, telephone progress, and telecommunications research and history. At least 15 of the films are available online at the Nokia Bell Labs, AT&T Archives, and other websites (see Fig. 47 and Fig. 48).

The public's imagination had been captured. Keychains, pins, broaches, and other giveaways were available. For example, the Chesapeake and Potomac Telephone Company of West Virginia issued magic sponges that expanded when dipped in water (see Fig. 49). Military engineers gave Telstar and Echo plenty of attention as they studied the technology and the implications of communicating in space as another way of "keeping in touch" to "keep the peace" using a global network of "reliable

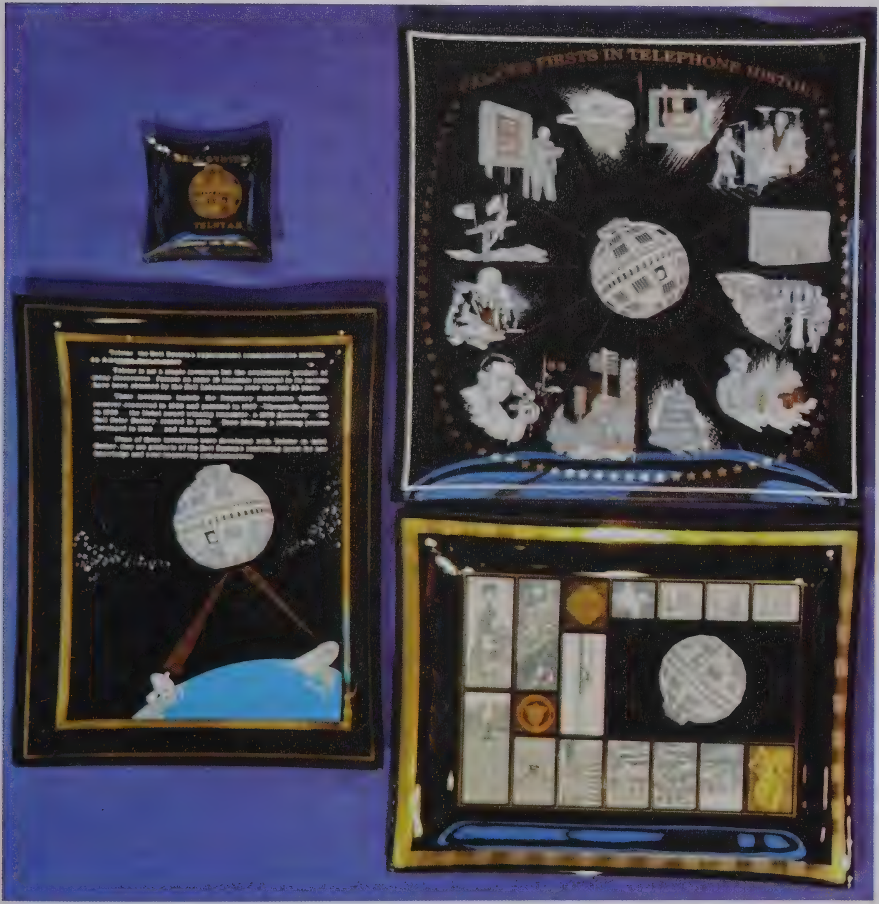


Fig. 47. Commemorative plates from AT&T and Bell Laboratories featuring Telstar and the history of telecommunications. (Authors' collection)

communications links of high quality."[94] Meanwhile, NASA publications continued to feature the Echo and Telstar satellites as NASA projects, blurring the line between NASA's interests and those of private enterprise.[95] It seemed that everyone was following Telstar. A March 1965 Archie comic book cover even showed three girls listening to a portable radio that was broadcasting "The First Beatle Program From Telstar!" where the satellite was beaming the lyrics to "Can't Buy Me Love."[96] Two months later in May 1965, the VHF transmitter in Telstar 2 was turned off.[97]

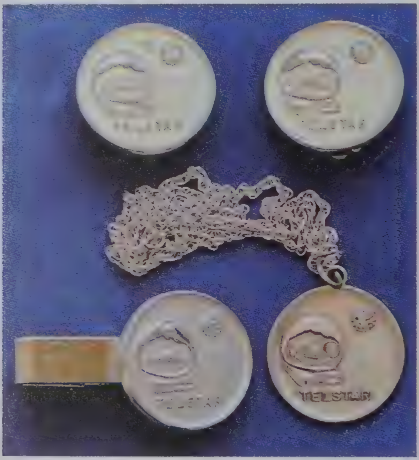


Fig. 48. Telstar satellite commemorative pendant, tie clasp, and cufflinks showing the Andover radome and horn antenna. (Authors' collection)

Telstar had indeed launched a new era in communications and a new era in the public's awareness of commercial satellites. For years, the public would refer to all communications satellites as "Telstars."[98]

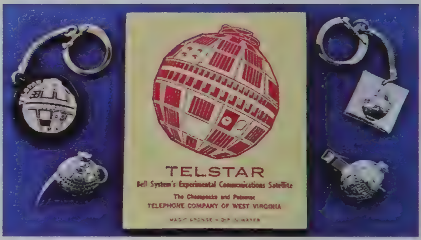

TELSTAR
Bell System's Experimental Communications Satellite
The Chesapeake and Potomac
TELEPHONE COMPANY OF WEST VIRGINIA

Fig. 49. Telstar sponge from Chesapeake and Potomac Telephone Company of West Virginia, broach (lower left), tie clasp (lower right), and key chains. (Authors' collection)

PART IV. LEGACIES OF THE HORN ANTENNAS

Echo and Telstar Satellites

Both of the original Project Echo satellites decayed in space: Echo 1 by 1968 and Echo 2 by 1969.[99]

Unfortunately, an increase in the energy level of the Van Allen radiation belt damaged Telstar 1. The American Starfish Prime high-altitude nuclear test on July 9, 1962, the day before launch, and three subsequent Soviet nuclear tests, in October and November 1962, contributed to a cumulative dose produced by high-energy electrons that damaged Telstar's transistors and solar cells. It went out of service in November 1962, restarted briefly in January 1963, and then shut down permanently in February 1963.[100] Nevertheless, all of the experiments intended for Telstar were completed.[101]

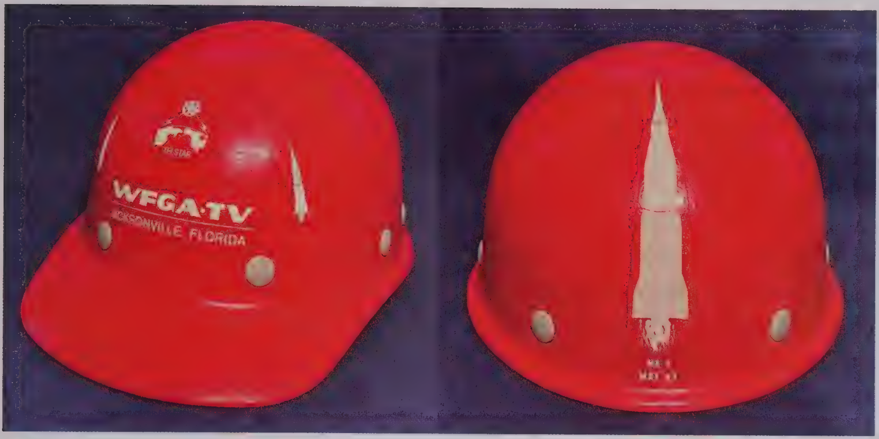


Fig. 50. Hardhat from WFGA-TV in Jacksonville, Florida with an image of Telstar 2 (front) and the Thor-Delta rocket (back) for the launch of Telstar 2 on May 7, 1963. (Authors' collection)

Telstar 2 launched in May 1963 (see Fig. 50). It was nearly identical to Telstar 1 but incorporated radiation-hardened transistors. It operated successfully for two years.[102] Both Telstar 1 and Telstar 2 remain in orbit today.[103]

Bell Laboratories and AT&T

The legendary Bell Telephone Laboratories began at the Western Electric Engineering Department in New York City. In 1925, the Engineering Department was reorganized into Bell Telephone Laboratories to consolidate research and development activities in the communications field and allied sciences. The new entity was placed under the shared ownership of AT&T and Western Electric. John J. Carty, the vice president of AT&T, became the first chairman of the board of directors, and the first president was Frank B. Jewett.[104] By the late 1950s, Bell Laboratories employed thousands of people in multiple locations across the country. In 1961, the old Holmdel research facility was replaced by a six-story, landmarked modern building designed by Eero Saarinen. Expanded twice, this facility grew to over 2 million square feet and served as the home to nearly 6,000 engineers and researchers.[105] In 35 years, Bell Laboratories had exploded in size and had developed an international reputation for its leading-edge research.

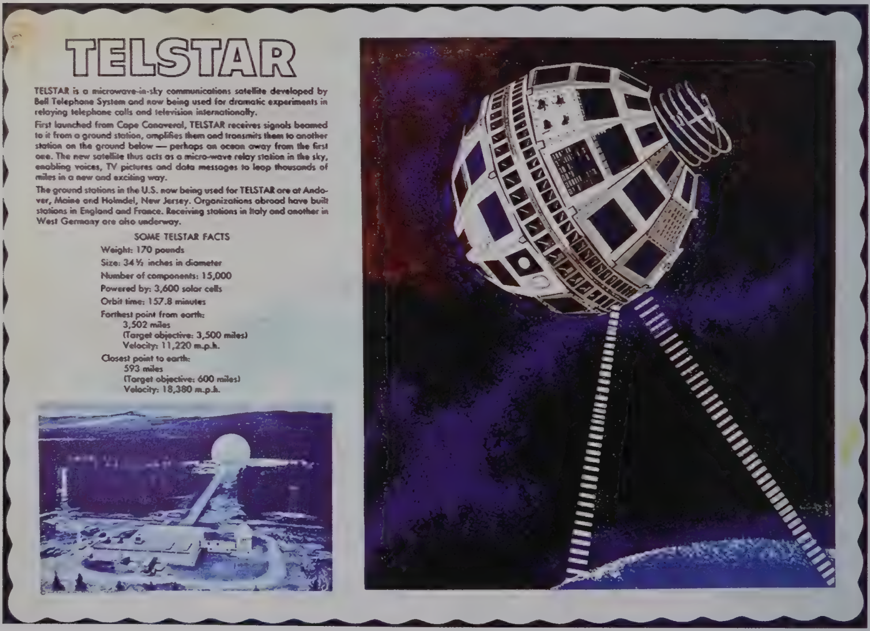
Project Echo and Project Telstar were conceived by Bell Laboratories and AT&T as experimental programs. Hundreds of Bell Laboratories and AT&T personnel and subcontractors worked on Project Telstar, and many had also worked on Project Echo (see Table 1). In addition, many Americans were among the more than 300 engineers who worked at the Pleumeur-Bodou installation in France. Hundreds of people were involved at NASA and other government agencies and at the civilian enterprises associated with the launch and operation of Telstar. These people contributed toward an astonishing accomplishment in communications and went on to the rest of their careers, spreading their knowledge, and further spreading the legacy and influence of Bell Laboratories and AT&T (see Fig. 51).[106]

In 1996, AT&T divested itself of most of Bell Laboratories and its equipment manufacturing company, Western Electric, by forming a new company, Lucent Technologies. AT&T retained a small number of researchers, forming AT&T Laboratories. In 2006, Lucent merged with Alcatel, forming Alcatel-Lucent. The following year, the former Bell Laboratories and the former Research and Innovations division of Alcatel were combined into a single organization, Nokia Bell Labs.[107]

The Holmdel facilities were closed in 2007 and sold to a developer. Since 2013, the building has operated as a multipurpose living and working space and a mixed-use office for high-tech startup companies called Bell Works.[108] In January 2021, Nokia sold the Crawford Hill facility and relocated its remaining Nokia Bell Labs research staff to its Murray Hill campus.[109]

The Holmdel Horn Antenna

The Holmdel Horn Antenna and its other ground stations performed successfully in the Project Echo experiments. "The Echo experiments produced the first two-way telephone conversations via satellite. They also confirmed predictions of the radio path loss to be encountered, the



TELSTAR

TELSTAR is a microwave-in-sky communications satellite developed by Bell Telephone System and now being used for dramatic experiments in relaying telephone calls and television internationally.

First launched from Cape Canaveral, TELSTAR receives signals beamed to it from a ground station, amplifies them and transmits them to another station on the ground below — perhaps an ocean away from the first one. The new satellite thus acts as a micro-wave relay station in the sky, enabling voices, TV pictures and data messages to leap thousands of miles in a new and exciting way.

The ground stations in the U.S. now being used for TELSTAR are at Andover, Maine and Holmdel, New Jersey. Organizations abroad have built stations in England and France. Receiving stations in Italy and another in West Germany are also underway.

SOME TELSTAR FACTS

Weight: 170 pounds
Size: 34 ½ inches in diameter
Number of components: 15,000
Powered by: 3,600 solar cells
Orbit time: 157.8 minutes
Farthest point from earth:
  3,502 miles
  (Target objective: 3,500 miles)
  Velocity: 11,220 m.p.h.
Closest point to earth:
  593 miles
  (Target objective: 600 miles)
  Velocity: 18,380 m.p.h.

Fig. 51. Pictorial placement from Bell Laboratories cafeteria featuring Andover Earth Station and Telstar, circa May/June 1962 pre-launch. (Authors' collection)

stability of the radio medium, and the low noise picked up by a well-designed antenna pointing at the sky…The Echo experiments opened the possibility of applying microwave radio relay technology to transoceanic links."[110] Echo's success led to joint commitments by AT&T and NASA for pursuing Telstar as a commercial effort that was supported by government infrastructure.[111]

In 1965 while using the Holmdel Horn Antenna on Crawford Hill for research regarding Telstar's radio signals and receiver interference, two radio astronomers, Dr. Arno Penzias and Dr. Robert W. Wilson (see Fig. 52) discovered that cosmic microwave background radiation (CMBR) permeates the universe.[112] "They removed the effects of radar and radio broadcasting, and suppressed interference from the heart in the receiver itself by cooling it with liquid helium to −269 °C, only 4 °C above absolute zero, the temperature at which all motion in atoms and molecules stops."[113] Their discovery provided evidence that confirmed George Gamow's and Georges Lemaître's Big Bang Theory about the creation of the universe. Penzias and Wilson made further modifications to the Holmdel horn antenna and the dish antennas at Holmdel in 1966 and 1968, enabling them to make additional measurements that further confirmed the galactic center of the universe.[114] Penzias and Wilson received the 1978 Nobel Prize in Physics

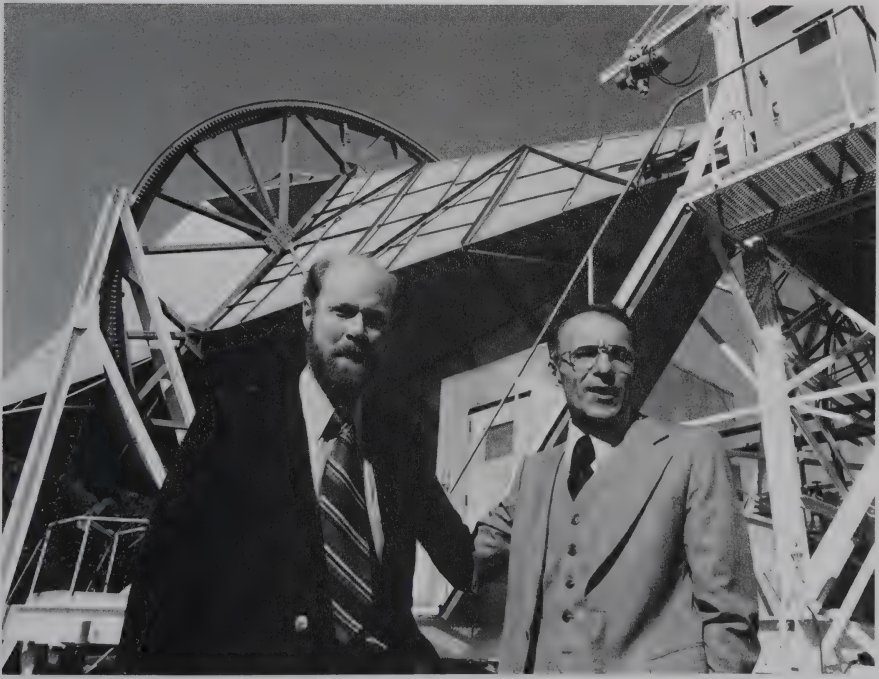


Fig. 52. Robert Wilson (left) and Arno Penzias (right) at the Holmdel horn antenna. (Courtesy Associated Press)

for their discovery.[115] Wilson explained the importance of the Holmdel antenna in his Nobel Prize acceptance speech, stating: "Traveling-wave maser amplifiers were available for use with the 20 foot horn-reflector, which meant that for large diameter sources (those subtending angles larger than the antenna beamwidth), this would be the world's most sensitive radio telescope."[116]

The Holmdel Horn Antenna on Crawford Hill was designated a National Historic Landmark in 1988 because of its association with Penzias, Wilson, and the Nobel Prize.[117] It still stands along with several other non-operating satellite dishes and old support buildings atop Crawford Hill, which is accessible to the general public. However, it sits on private land, and it is at risk of redevelopment, even though the site is currently zoned for research.[118] All of the equipment from inside the antenna and the nearby building that housed the controls has been removed (see Fig. 53).

The Andover Horn Antenna and Related Sites

Following Telstar, the Andover Earth Station in Maine became an immediate tourist attraction (see Fig. 54). Initially, AT&T permitted visitors to enter the radome but due to the crowds, AT&T soon installed a large picture window in the wall of the concrete base to allow visitors to view the antenna from outside the radome. Postcards, commemorative stamps, and souvenirs were produced

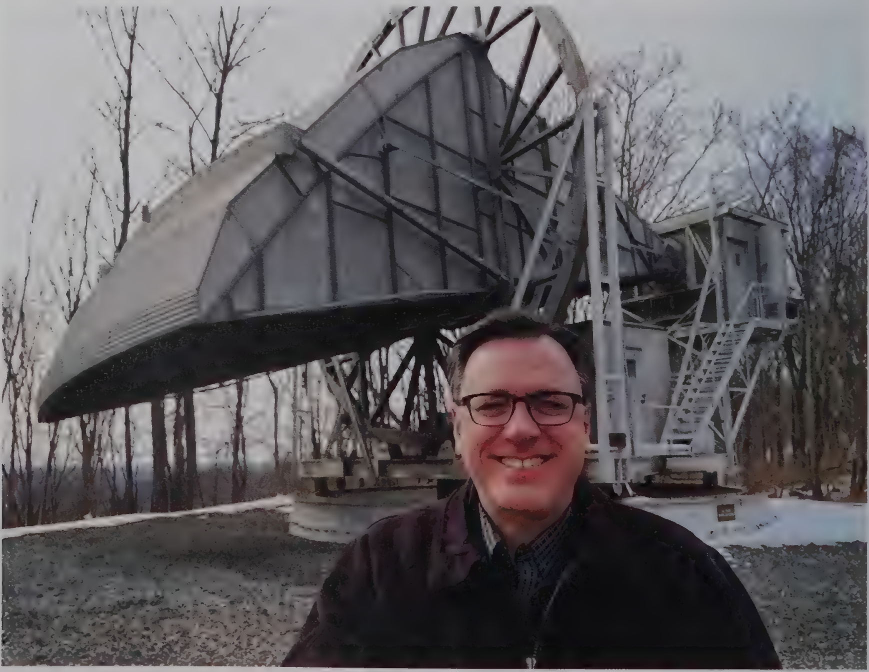


Fig. 53. Author by the Holmdel horn antenna at Crawford Hill in 2019. (Authors' photo)

by many countries, and Bell Laboratories and AT&T featured Telstar in their exhibits at the World's Fairs held during the 1960s (see Fig. 55 and Fig. 56).

Bell Laboratories and AT&T operated the Andover Earth Station and the large horn antenna in conjunction with their own development of satellites, but this was short-lived. Following the August 17, 1962, signing of the Communications Satellite Act of 1962 and the creation of the Communications Satellite Corporation (Comsat), Comsat became the systems manager for the International Telecommunications Satellite Consortium (Intelsat).[119] Thus, AT&T exited the satellite tracking business; it rapidly wound down its satellite staff, and Comsat acquired the Andover Earth Station from AT&T in 1965[120] (see Fig. 57). Nevertheless, the horn antenna proved to be highly versatile, and was used for the Relay, Syncom, and Intelsat 1 (named Early Bird) satellites. When it was no longer convenient to use the separate VHF transmission antenna, the horn was fitted for transmission and reception tracking feeds at seven different frequencies from 123 to 7360 MHz.[121]

Fig. 54. Cover of Bell Laboratories tourist brochure for the Andover Earth Station showing the entry sign. (Authors' collection)

By 1980, the Andover Earth Station was no longer using the radome or the horn antenna. The radome was torn down and the land was restored to nature in 1985.[122] MCI International, a unit of MCI Communications Corp., purchased the Andover Earth Station in 1987.[123] MCI was later purchased by Verizon in 2006, which included acquisition of the Andover Earth Station.[124] Today, the station continues to support satellite operations for Verizon.[125]

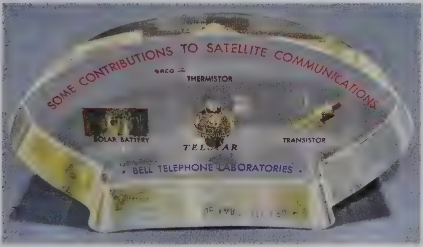

SOME CONTRIBUTIONS TO SATELLITE COMMUNICATIONS
THERMISTOR
SOLAR BATTERY
TELSTAR
TRANSISTOR
BELL TELEPHONE LABORATORIES

Fig. 55. Lucite souvenir from the Bell Telephone Laboratories display at the New York World's Fair, 1964, highlighting contributions to satellite communications: solar battery cell, thermistor, transistor, and Telstar. (Authors' collection)

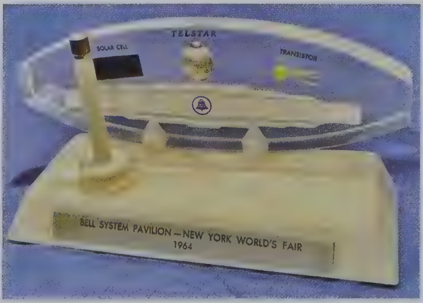


Fig. 56. Lucite souvenir from the AT&T Bell System pavilion at the New York World's Fair, 1964, highlighting an alloy junction gold transistor, early solar cell and Telstar. (Authors' collection)

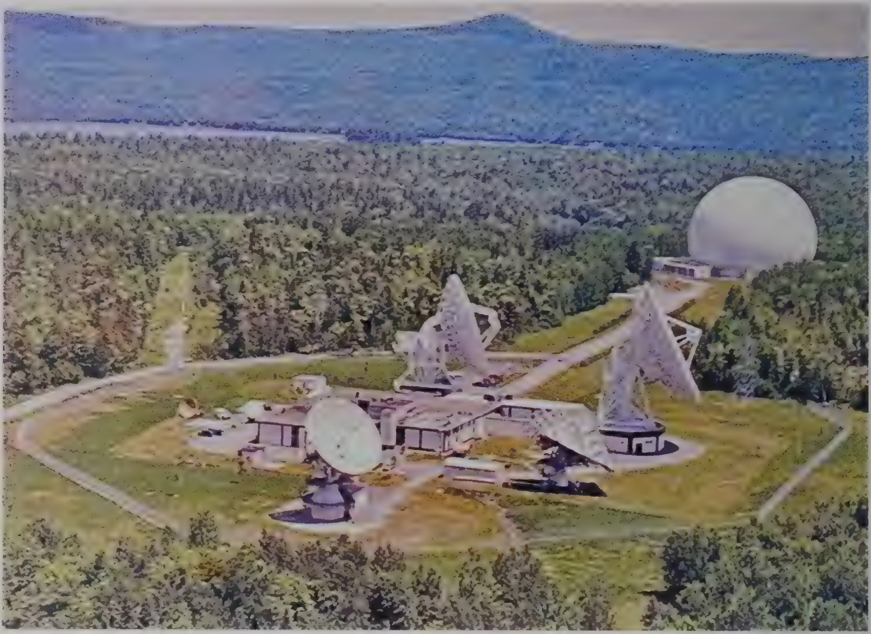


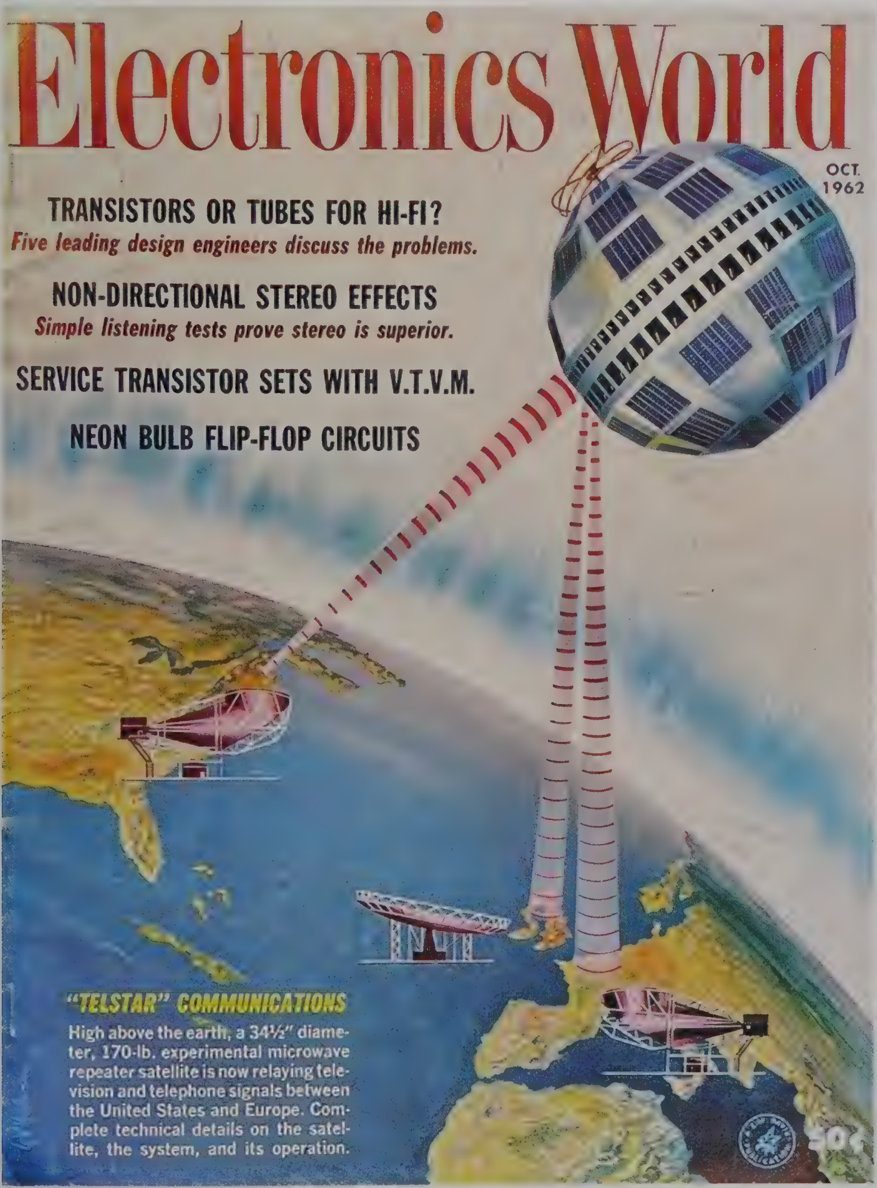
Fig. 57. Postcard of Andover Earth Station operated by Comsat circa 1975–1980. (Authors' collection)

In April 1961, AT&T, Bell Laboratories, NASA, the British Post Office (BPO), and the French National PPT (Post Office) signed a multi-national agreement (Agreement) establishing joint collaboration for the project development of two active, mobile telecommunications satellites, "Telstar" and "Relay."[126] Under the Agreement, two main European satellite locations were constructed for the Telstar Project. Smaller systems were installed in Germany and Italy (see Fig. 58).

Goonhilly-Downs in western Cornwall, England was selected for an antenna location due to its westernmost location in the United Kingdom, its topography, and its remote location that was relatively free of radio interference. The first satellite antenna built on the site, Goonhilly 1, also known as Arthur, was a parabolic dish design weighing 1,118 tons and was 92 feet in diameter. It set a world standard for the open parabolic design of the dish.[127] Until 2006, the Goonhilly Satellite Earth Station was the largest satellite receiving station in the world with over 60 antenna dishes. That year, the facility was closed, and its operations were relocated to the Madley Communications Centre in Herefordshire. The Goonhilly visitor center and its exhibits were shuttered in 2010 (see Fig. 59).[128]

The designs from the Andover Horn Antenna and radome were replicated in Pleumeur-Bodou, France (northeast of Brest). That site was selected for reasons similar to the Andover site selection: its proximity to the new National

Telecommunications Research Center (CNET) laboratories, which was responsible for overall operation; the absence of radio interference; its geographical position on the western coast of France; and its mild climate. The site design was nearly identical to Andover. The first radome was only temporary and was



Electronics World

OCT. 1962

TRANSISTORS OR TUBES FOR HI-FI?

Five leading design engineers discuss the problems.

NON-DIRECTIONAL STEREO EFFECTS

Simple listening tests prove stereo is superior.

SERVICE TRANSISTOR SETS WITH V.T.V.M.

NEON BULB FLIP-FLOP CIRCUITS

"TELSTAR" COMMUNICATIONS

High above the earth, a 34½" diameter, 170-lb. experimental microwave repeater satellite is now relaying television and telephone signals between the United States and Europe. Complete technical details on the satellite, the system, and its operation.

50¢

Fig. 58. Cover of *Electronics World*, Oct. 1962, featuring the three main antenna sites for Telstar.

installed to house the construction site for the antenna. Both this temporary shelter and the final radome measured 210 feet in diameter. The final radome and horn antenna were installed in the summer of 1962. Like Andover, the radome is made of Hypalon-coated Dacron and weighs over 30 tons. The antenna remained operational until 1985. The radome and antenna are now

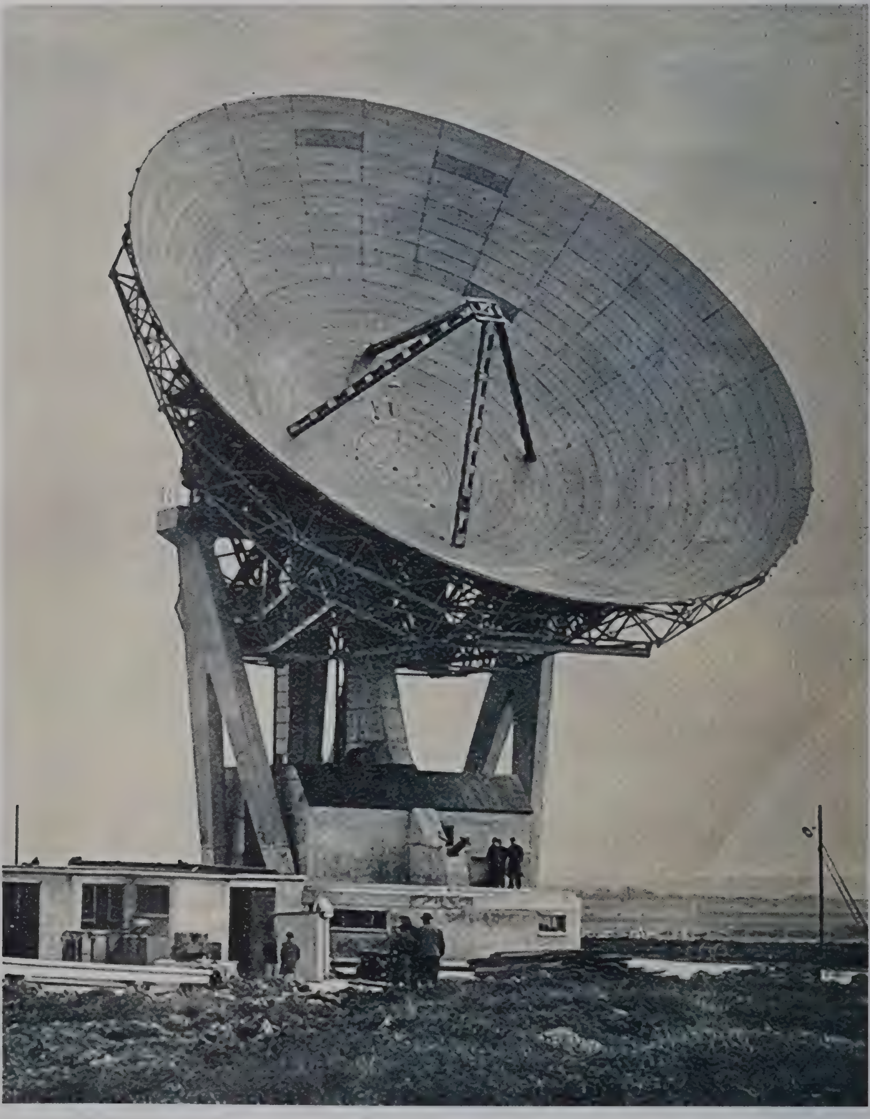


Fig. 59. Dish antenna at Goonhilly-Downs, Cornwall, England circa 1961. (Courtesy British General Post Office)

a museum and national monument operated under the auspices of France Telecom that receives more than 100,000 visitors each year (see Fig. 60).[129]

The Institute of Electrical and Electronics Engineers (IEEE) commemorates significant technical achievements within its fields of study through its Milestones program. The Milestone plaque at Bell Laboratories in Murray Hill, New Jersey lists Telstar as one of ten major accomplishments of "BELL LABS - WIRELESS AND SATELLITE COMMUNICATIONS, 1925–1983." Three nearly identical IEEE Milestones were part of a triple dedication in 2002, the 40th anniversary of Telstar. They are located at Andover; Pleumeur-Bodou, France; and Goonhilly Downs, Cornwall, England. All used similar wording to mark the "FIRST TRANSATLANTIC RECEPTION OF A TELEVISION SIGNAL VIA SATELLITE, 1962." The plaque at Pleumeur-Bodou reads: "On 11 July 1962 this site received the first transatlantic transmission of a TV signal from a twin station in Andover, Maine, USA via the TELSTAR satellite. The success of TELSTAR and the Earth stations, the first built for active satellite communications, illustrated the potential of a future worldwide satellite system to provide communications between continents." The Andover plaque states the signal was transmitted to a twin station in Pleumeur-Bodou. Beginning in 2013, IEEE issued commemorative coasters celebrating various historic IEEE Electrical Engineering Milestones, including one for Telstar (see Fig. 61).

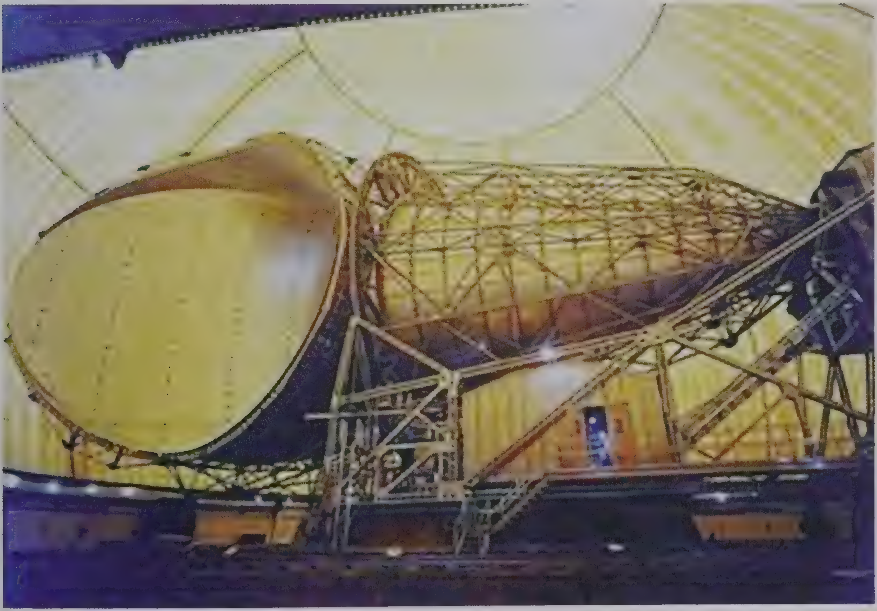


Fig. 60. The horn antenna at Pleumeur-Bodou, France, now the Museum of Telecommunications. (Courtesy 16th International EME Conference 2014, IEEE ETHW)

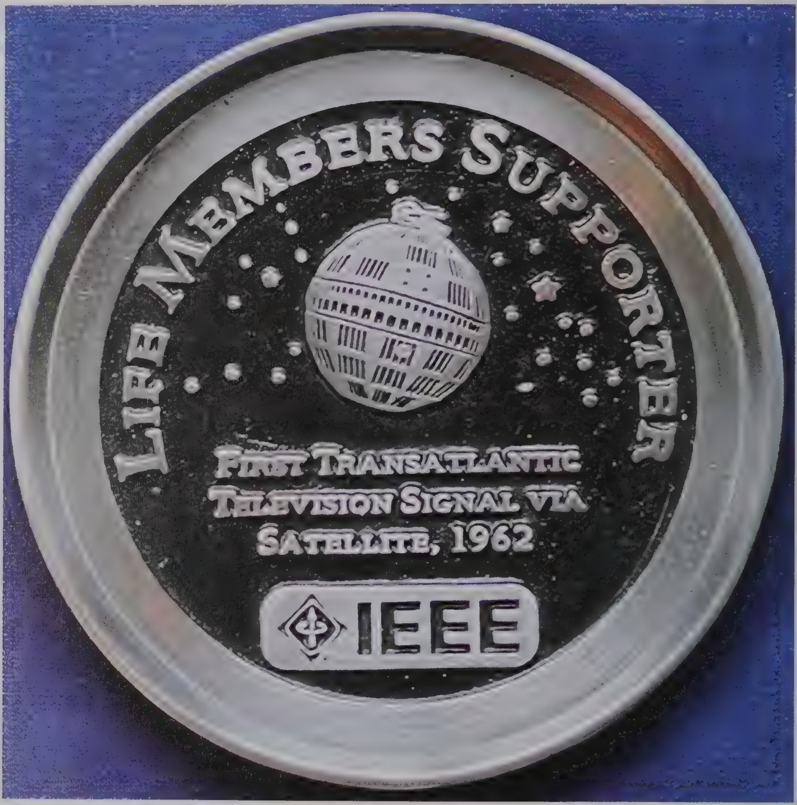


Fig. 61. IEEE commemorative coaster celebrating Telstar. (Authors' collection)

Satellite Development

Echo 1 and Telstar led the way in joint efforts by the U.S. government and industry to develop and build satellites. NASA and the Radio Corporation of America launched a separate medium-orbit (4,000 miles) communications satellite called Relay 1, which was the first satellite to transmit programs between the United States and Japan.[130] Hughes Aircraft Company produced Syncom, a satellite with a 20,000 mile orbit that circled the Earth in 24 hours. By 1964, two Telstars, two Relays, and two Syncoms were all successfully operating. Comsat launched its own radio-relay satellite, Intelsat 1 (or Early Bird) for the International Telecommunications Satellite Organization (Intelsat) in April 1965.[131]

AT&T constructed numerous ground receiving stations for its Telstar program together with its global telephone and telegraph cable partners. NASA partially relied on this network of stations for tracking the Relay and Syncom satellites. By the time of Early Bird, ground stations existed in the United Kingdom, France, Germany, Italy, Brazil, Japan, and the United States. The previous year, in August 1964, Intelsat had been formed to own and manage this global system.[132] Yet, even today, the image of Telstar remains an iconic symbol of international satellite cooperation.

Numerous studies by major communications companies documented the tremendous economic potential for commercial satellites in the late 1950s and early 1960s.[133] The economics of operating satellites provided significant incentives for their development, and their communications capacities increased with each innovation. For example, Early Bird provided nearly ten times the capacity of submarine telephone and telegraph cables for one-tenth the cost. Satellites also proved more reliable (although unlike subsea cables, they could not be repaired), and they could be used for point-to-point communication or point-to-multipoint broadcasting. These economics were not matched until the first fiber-optic transatlantic telephone cable was laid in 1988, TAT-8.[134]

Today, the U.S. government and commercial enterprises operate 36 satellites and innumerable ground stations that provide services exclusively to the United States. Over 300 communications satellites are now in orbit worldwide. Cellular technology has brought even newer options for managing entire personal communications systems comprising voice and data. These satellites operate in lower Earth orbits than Telstar, only 500 miles above the earth, far below the Van Allen radiation belt.[135]

SpaceX, a private company, developed the Starlink satellite internet constellation that provides satellite internet access coverage to 45 countries. SpaceX plans to use Starlink for global mobile phone service after 2023.[136] SpaceX began launching Starlink satellites in 2019. As of December 2022, Starlink includes more than 3,300 mass-produced small satellites operating in low Earth orbit (LEO), which communicate with designated ground transceivers.[137] SpaceX intends to deploy nearly 12,000 total satellites, with a later extension of up to 30,000 additional satellites.[138] In December 2022, SpaceX announced it had reached more than one million subscribers.[139]

None of this would have been possible without the early successes of Echo 1, Telstar 1, and the foundations laid by the accomplishments of the Bell Laboratories ground stations at Holmdel and Andover. In 1958, NASA concluded that it needed "a network of linked stations, capable of receiving, processing, and reacting to a variety of voice, radar, and telemetry data."[140] On July 30, 1959, nearly three years before Telstar 1, NASA awarded the contract for creating an integrated spacecraft tracking and ground instrumentation system to Western Electric Company. Bell Laboratories became responsible for systems engineering and command and control functions. That knowledge led to the development of Telstar's systems, and eventually contributed to the Mercury and Apollo manned flight communications systems.[141]

The evolution and expansion of these early communications systems in their first years was enormous, and the technological advances they relied upon were spectacular. As a NASA historian explained in 1989, "Before these satellites existed, the total capability for transoceanic telephone calls had been 500 circuits; in 1973 [just over ten years after Telstar] the Intelsat satellites alone offered more than 4,000 transoceanic circuits. [And,] real-time TV coverage of events anywhere in the world…had become commonplace in the world's living rooms."[142] What would he say about today's satellites, just over thirty years later, that now operate in a digital world (see Fig. 62)?

Endnotes

1. For an in-depth discussion about these early satellites and the development of their internal tube and solid-state technologies (Sputnik 1, Explorer 1, Vanguard 1, and Telstar 1), see D. Bart and J. Bart, "Early Milestones in Space Communications," *AWA Review*, Vol. 32, 2019, pp. 165–214.
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3. President Eisenhower signed the National Aeronautics and Space Act of 1958 on July 29, 1958, establishing NASA, which absorbed the earlier National Advisory Committee for Aeronautics (NACA) that had been undertaking, promoting, and institutionalizing aeronautical research since 1915. NACA dissolved on October 1, 1958, and its assets and personnel formed the core of the

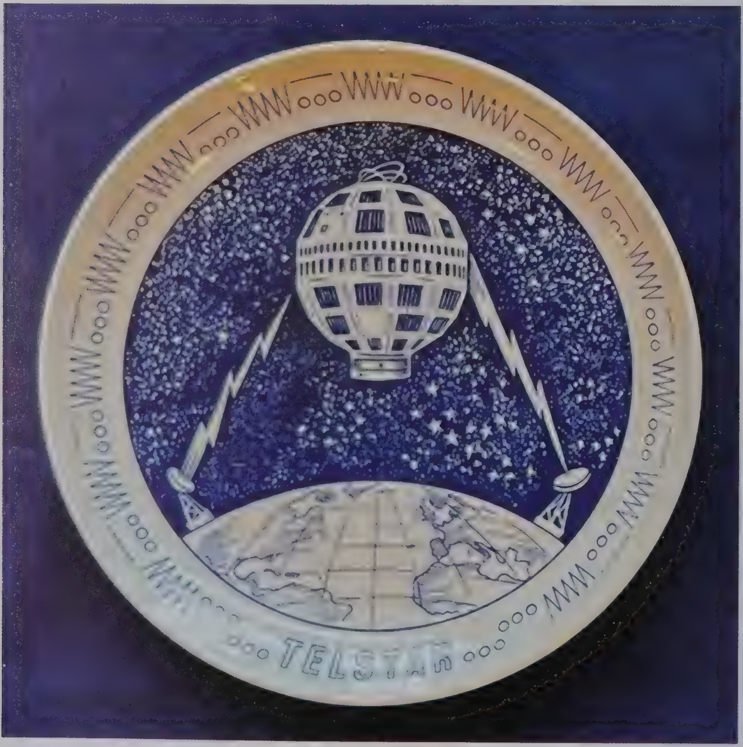

Fig. 62. Telstar 10th anniversary plate by the Kensington Line, Denmark, BYGDO, 1972. (Authors' collection)

newly created NASA. See R. E. Bilstein, *Orders of Magnitude A History of the NACA and NASA, 1915–1990,* (Washington: NASA, NASA Historical Series, SP 4406, 1989) pp. 1–4, 48–49.

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6. See notes 4 and 5.
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8. R. L. Rosholt, *An Administrative History of NASA, 1958–1963,* (Washington: NASA, Scientific and Technical Information Division, 1966, SP-4101) p. 175; Chronology of Major NASA Launches Oct. 1, 1958, through Dec. 31, 1962 (Washington: NASA, Office of Educational Programs and Services, Jan. 1963).
9. "Project Telstar Background to Satellite Communications: Radio, Cables, Microwave," Unpublished Project Telstar Press Relations Folder, Dave Manahan, 1962. Note, Mr. Manahan was an AT&T public relations executive. He possessed an unpublished press relations folder and a separate unpublished press relations binder of Telstar materials, which are separately designated (Authors' collection). See also G. Fuller, "AT&T Long Lines: A Forgotten Tale," at http://personal.garrettfuller.org/blog/2018/01/19/att-long-lines-a-forgotten-system/.
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12. D. C. Elder, *Out From Behind The Eight-Ball: A History of Project Echo,* (San Diego: American Astronautical Society, 1995) pp. 3–6; Gertner, 2012, p. 210.
13. W. C. Jakes, "Participation of Bell Telephone Laboratories in Project Echo and Experimental Results," *The Bell System Technical Journal,* July 1961, Vol. 40, pp. 975–1028; S. Millman ed., *A History of Engineering and Science in the Bell System: Communications Sciences 1925–1980,* (Indianapolis: AT&T Bell Labs, 1984) p. 226; Gertner, 2012, pp. 210–214.
14. Ibid.
15. Ibid., p. 51; J. M. Logsdon ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program,* (Washington: NASA History Office, 1998) Vol. III, p. 2.
16. J. R. Hansen, *Spaceflight Revolution,* (Washington: NASA History Series, SP-4308, 1995) pp. 159–161.
17. Butrica, 1997, Ch. 4.
18. Jakes, 1961, p. 995.
19. L. Jaffe, "NASA Communications Satellite Program," in *Proceedings of the Second National Conference on the Peaceful Uses of Space,* Seattle, WA, May 8–10, 1962, (Washington: NASA, SP-8, 1962) pp. 106–109.
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21. Logsdon, *Exploring the Unknown,* Vol. III, p. 3.
22. J. R. Pierce, "Communication Satellites," *Scientific American,* Vol. 205, No. 4, Oct. 1961, p. 101.
23. Gertner, 2012, pp. 218–219.
24. Elder, 1995, pp. 55, 137, 143.
25. Ibid., pp. 86–87.
26. Gertner, 2012, p. 219; Project Telstar Background to Satellite Communications, D. Manahan, 1962.
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28. G. Oakley, *Project Telstar,* (London: W. Foulsham & Co. Ltd., 1963) p. 34; "Telstar Project Officials," Project Telstar Press Relations Folder, D. Manahan, 1962.
29. The Bell System's Project Telstar, p. 4.
30. Gertner, 2012, p. 221.
31. Bell Laboratories manufactured and NASA launched the first two Telstars, which had nearly identical designs. The remaining four Telstar satellites were completed and were flightworthy, but they were never launched. In 1980, AT&T contracted with Hughes Space and Communications Group for Hughes to construct a new group of Telstar satellites that were launched beginning in 1983. These were named after Telstar 1 and 2 but were not part of the original series. "Telstar 301, 302, 303 / Arabsat 1E," Gunter's Space Page website, https://space.skyrocket.de/doc_sdat/telstar-3.htm.

32. Butrica, 1997, Ch. 6 and 9; The Bell System's Project Telstar, p. 5.
33. J. R. Pierce, "Exotic Radio Communications," *Bell Laboratories Record*, Sept. 1959, p. 323 reprinted in Logsdon, *Exploring the Unknown*, Vol. III, p. 22.
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36. *Bell Laboratories Record*, Special Telstar Issue, Apr. 1963, p. 119.
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38. The Bell System's Project Telstar, p. 3.
39. A. S. Gilmour. *Klystrons, Traveling Wave Tubes, Magnetrons, Crossed-Field Amplifiers, and Gyrotrons*, (Artech House, 2011) pp. 317–18.
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48. Bodmer, 1963, pp. 1703–1748.
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50. W. Cronkite, "Telstar," NPR Broadcast, https://www.youtube.com/watch?v=FgplIWibv4Q.
51. Martin, 1991, p. 10.
52. L. Jaffe, *Communications in Space*, (New York: Holt, Rinehart and Winston, 1966) p. 107.
53. Gertner, 2012, pp. 213–214.
54. Butrica, 1997, Ch. 5. Note, the Pioneer program encompassed two sets of U.S. lunar and planetary exploratory space probes. The first program (1958–1960), unsuccessfully attempted to orbit the Moon, successfully flew past the Moon, and successfully navigated the interplanetary orbital space between Earth and Venus. The second program (1965–1992) sent a series of spacecraft to measure interplanetary space weather, including outer planet probes Pioneer 10 and Pioneer 11, which became the first two artificial objects to leave the solar system.
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70. Dolling et al., July 1963, pp. 1142, 1150.
71. Ibid., p. 1152.
72. Ibid., p. 1153.
73. Ibid., pp. 1148–1150.
74. Ibid., p. 1157.
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76. Dolling et al., July 1963, p. 1173.
77. Ibid., p. 1177.
78. Ibid., pp. 1179–1180; O'Neill, 1985, p. 387.
79. Magazine advertisement from B. F. Goodrich circa 1964. (Authors' collection)
80. Smith et al., July 1963, pp. 1416–1417.
81. Dolling et al., July 1963, p. 1137.
82. Smith et al., July 1963, p. 1402.
83. Dickieson, 1963, pp. 743–744; W. C. Jakes, "Participation of the Holmdel Station in the Telstar Project," *The Bell System Technical Journal*, July 1963, Vol. 42 No 4, Part 2, pp. 1421–1423; Smith et al., July 1963, pp. 1383–1385; *Bell Laboratories Record*, Special Telstar Issue, Apr. 1963, pp. 123–125, 131–133.
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About the Authors

David and Julia Bart reside in the Chicago area. Together, they have published numerous articles on telegraph, radio, and broadcasting history. David has a BA and MBA from the University of Chicago. He is the National Director of the Restructuring and Complex Litigation Practice at Baker Tilly US LLP. He has published widely in his field and authored professional standards involving corporate finance and commercial litigation. David is a Director and Life Member of the Antique Wireless Association, and a former Co-Editor of the *AWA Review.* He is a Fellow, Life Member, and President of the Radio Club of America and serves as the Editorial Director of the *Proceedings of the Radio Club of America.* David is also Vice President of the Museum of Broadcast Communications in Chicago and Treasurer of the IEEE Historical Committee. He has received numerous awards for his historical research, publications, and exhibit development. He is the former President of the Antique Radio Club of Illinois.

Julia received her BA from the University of Chicago and MA from Concordia University, Chicago. She teaches elementary school with specialties in Reading and English Language Learning (ELL) instruction. Julia is a former Associate Editor of the *AWA Review* and an advisor to the Antique Wireless Association. She is a former officer of the Antique Radio Club of Illinois, editor of its publications, and an advisor to the board of directors. She has co-authored many peer-reviewed articles for the AWA, RCA, and IEEE and works closely with David on their collecting interests.

David and Julia Bart

Evolution of the TV Receiver

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Between 1929 and 1939, television grew from a laboratory curiosity to a commercially viable system. This paper will show, via one specific trail, how each iteration of the 'home' TV set made that transition (evolved?) in very deliberate steps. Here we define the television receiver as a complete package that receives radio-frequency transmitted audio and video images, complete with appropriate synchronizing information, and displays such images using a completely electronic system. The receivers described were developed by Radio Corporation of America.

The Year 1929

Vladimir Zworykin had been employed by Westinghouse Electric Corporation since the early 1920s. Unlike Alexanderson at General Electric, he intended to produce a non-mechanical television system. By late 1929, he was able to demonstrate an operating receiver, shown in Fig. 1.[1] Several receiving sets, each with a seven-inch diameter image tube, were constructed. Although vertical deflection was sawtooth, driving deflection plates, the horizontal deflection was sinusoidal driving deflection coils. SPU refers to socket power unit. Subsequent design change shows the transmission of video and sync by one carrier. The image was provided by mechanical means.

One of these sets was installed at Zworykin's home, located four miles from the transmitter. The sets were constructed in self-contained cabinets and operated on AC power. A demonstration was made to engineers on August 17, 1929.[2] The received image had a greenish hue and was composed of 60 lines at 12 frames per second. There is some debate concerning whether there were actual demonstrations of the set.[3]

A personal interview with Westinghouse engineer Ross Kilgore provides additional information. He related to me that he witnessed the set in operation

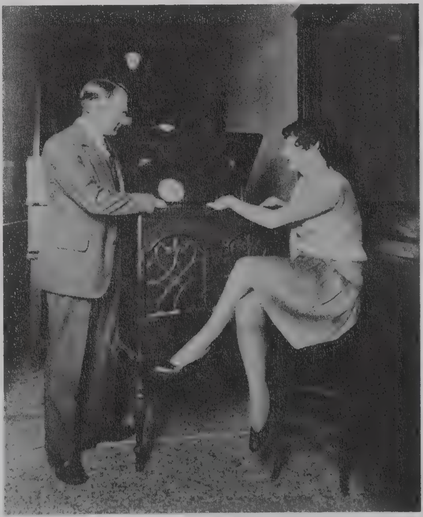


Fig. 1. A publicity photo of Zworykin with a 1929 TV set was taken in the old Westinghouse research lab on Ardmore Blvd. Seated is secretary Mildred Bird. (Westinghouse, *Zworykin, Pioneer of Television*)

and indicated that "…it had quite a good picture." He also confirmed the woman was Mildred Bird.[4]

The receiver circuitry was obtained from a crude sketch dated October 10, 1929, by engineer Harley Iams, an assistant of Dr. Zworykin. It defined the set as having two "radio sets," one for image and the other for synchronizing impulses (see Fig. 2).[5]

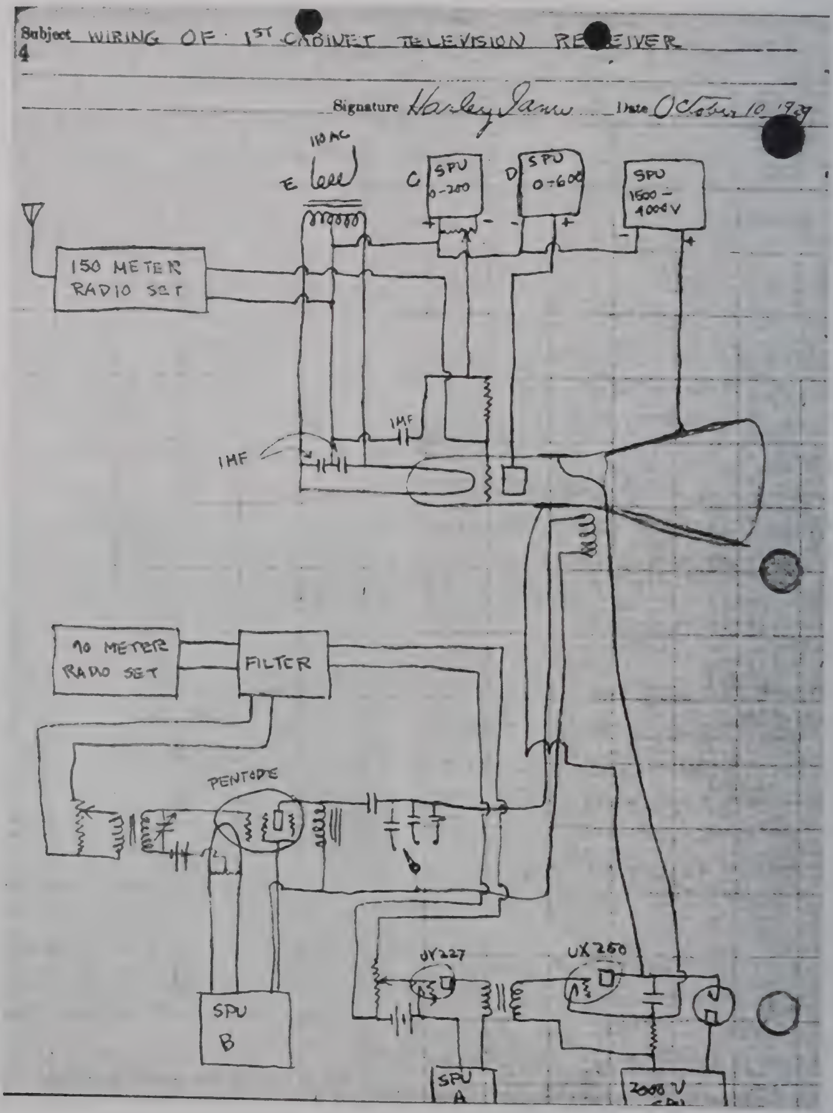


Fig. 2. This circuit diagram of the first cabinet television receiver shows that there was a separate transmission of sync and image signals. (Sketch by Harley Iams, October 10, 1929)

The Year 1932

This TV receiver was a component of a system that was "placed in operation… late in 1931" and demonstrated in May 1932 in New York City with images transmitted from the Empire State Building (see Fig. 3). It was reported that the images were "fairly clear."[6] A mechanical "flying spot" scanning system was used to generate a signal, and the receiver reproduced a 5½ × 6½ inch image of 120 lines at 24 frames per second.[7] Sound and picture each had superheterodyne receivers. Horizontal and vertical scanning was with a sawtooth waveform driving the deflection coils.

The Year 1933

The next television receiver, RC-58, shown in Fig. 4, was used in February 1933 when the iconoscope camera was first employed. One tuner was employed for both sound and picture. The 5⅞ × 7 inch image was composed of 243 lines, interlaced, at a frame rate of 30 per second.[8] The received image was described as having "…no apparent flicker…a studio closeup view now shows all facial expression, and small gestures are readily interpreted."[9] (Note: Interlacing is indicated in endnote 9, but not by either Abramson or Zworykin.)

The set was quite complex with separate mixer and IF channels for audio and video. There was no RF amplifier. The sound channel, 6 MHz, had three IF amplifiers, with the video, 7 MHz, having five. Both channels had AVC circuitry. Horizontal and vertical deflection circuits each had four tubes. Vertical deflection coils and horizontal deflection plates were employed. Audio

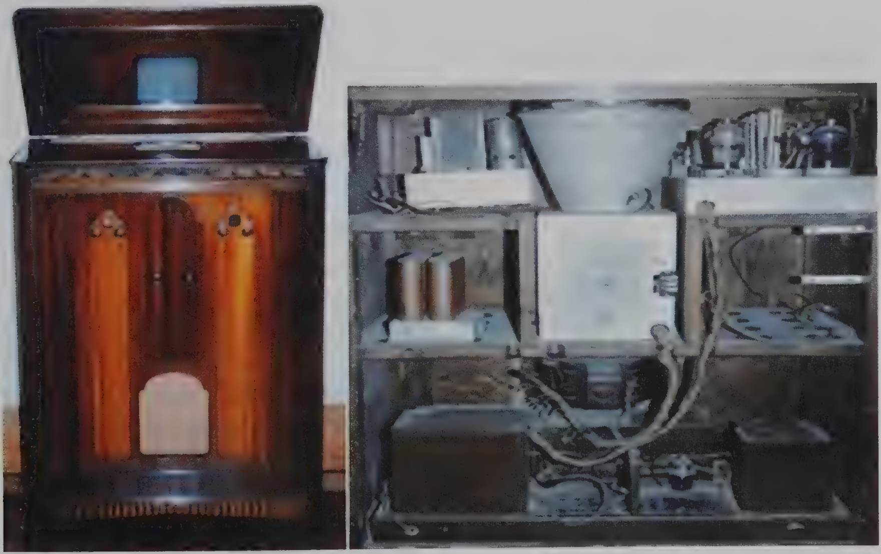


Fig. 3. This TV receiver dating to 1932 was a component of a system that was "placed in operation…late in 1931" and demonstrated in May 1932 in New York City with images transmitted from the Empire State Building. (J. Lendaro)

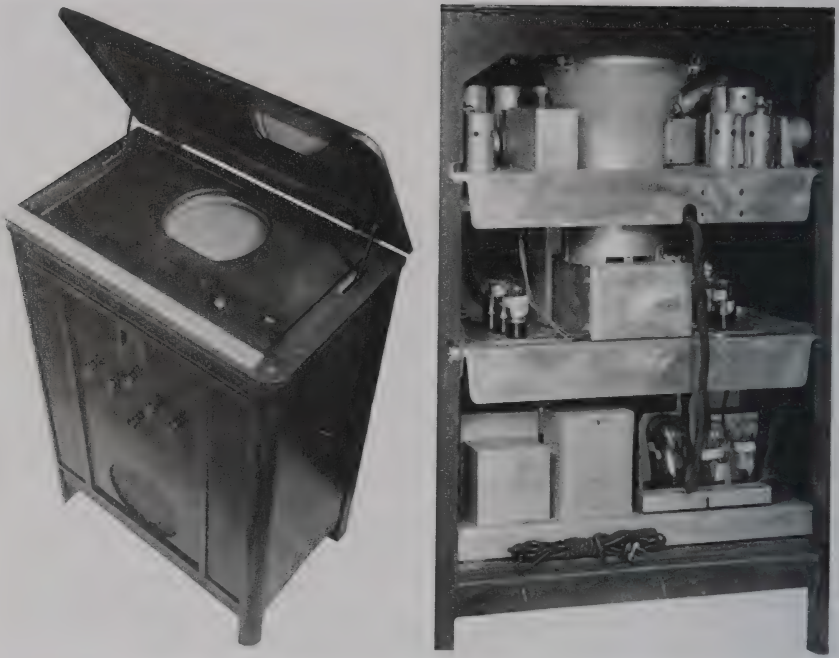


Fig. 4. This RC-58 television receiver was used in February 1933 when the iconoscope camera was first employed. (D. Hock)

was supplied by a pair of 45 tubes. Low voltage power was by two 83 tubes. A pair of special rectifier tubes, R-613, provided 4,600 volts to the second anode. The video amplifier had a gain of 10,000 and the response was essentially flat to 1 MHz.

The Year 1934

The RCA Victor Company, Inc. Research Division report *TR-244-C* describes a project to develop a "low-priced television receiver." The objective was: "To develop and build a sample television receiver having all the features essential to good performance, but substantially lower in estimated production cost than any receiver previously built."

Features included AVC and one-knob sound and picture tuning. Single sideband TV transmission had been developed, reducing the bandwidth requirement in the receiver. The resultant set used a shorter five-inch kinescope to allow a front mounting. The kinescope was cost-reduced by eliminating deflection plates. Scanning was increased from 243 to 343 lines, interlaced. The low-cost TV receiver is shown in Fig. 5.[10]

The five-inch tube required a lower second anode voltage, making for a less expensive high-voltage transformer. The picture IF amplifier was simplified by reducing bandwidth and eliminating a stage of gain. The AVC circuit was also

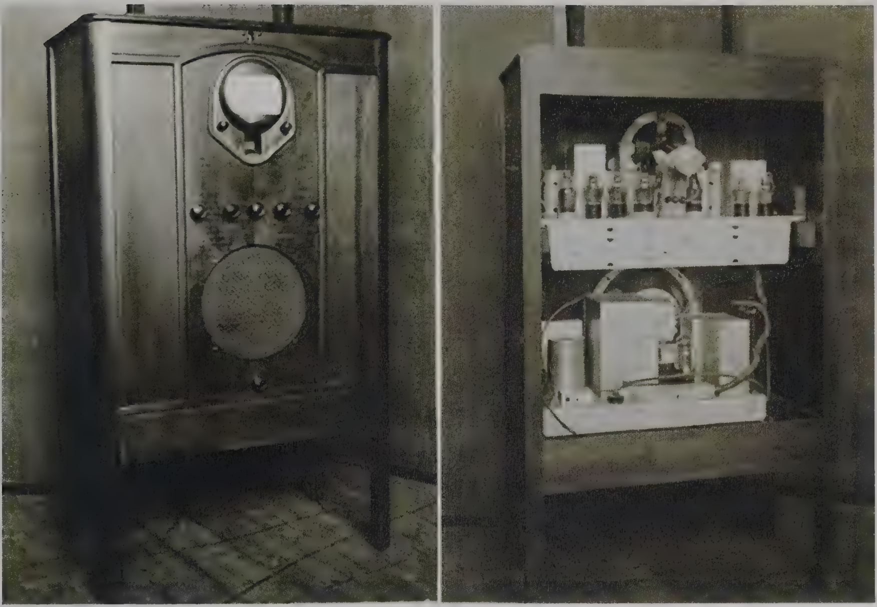


Fig. 5. The RCA Victor Company, Inc. Research Division developed this “low-priced television receiver” to meet their objective of demonstrating a sample television receiver having all the features essential to good performance, but with a substantially lower production cost than any receiver previously built. (Hagley Museum and Library)

simplified. The tube count was down to 19 located on two chassis units with separate subassemblies to facilitate manufacture. “Each IF stage is a complete subassembly, and can be built, tested, and aligned before it is mounted on the chassis…Other sub-assemblies are used in the deflecting circuits, and in the audio and video amplifiers.”

“Tests on the receiver show that its performance more than meets expectations, and that such a receiver will have a definite place in the line of television receivers marketed when television is introduced commercially.” Not mentioned was the fact that the received images had a greenish hue. A white phosphor CRT was not yet in service.

It should be obvious at this point that TV could have been commercialized in the United States in the mid-1930s. After all, in 1936, the London Television Service was initiated with an image of 405 lines, interlaced, at 25 pictures per second. This 405-line system continued in the UK for almost 50 years![11] The difference between 343 and 441 lines would be virtually unnoticeable with the small screens in use at the time.

The Year 1936

This RR-359 television set was used by RCA in 1936 to test and demonstrate electronic television in the New York area (see Fig. 6). According to an article in the *New York Times*: “The latest

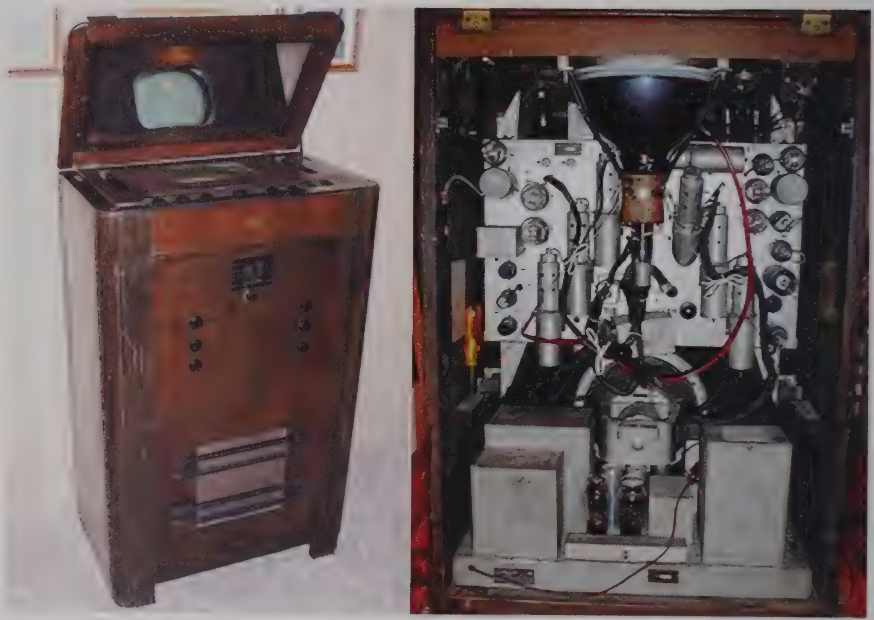


Fig. 6. This RR-359 television receiver was used by RCA in the New York City area in 1936 to test electronic television. (Early Television Foundation)

television receiver, at first glance, looks like an ordinary console radio…There are 33 tubes…14 control knobs…They regulate the sound, govern the brilliancy of the picture, focus, synchronism, center the image, regulate its size, and generally refine the image." The *New York Times* went on to explain that "The received picture is comprised of 343 interlaced lines designed to minimize flicker. The green tint of the picture is purposely arranged because the human eye is more sensitive to that color…" The article also stated: "Television spectators a mile across the city [of Camden] watched… a greenish-hued picture, 5 by 7 inches on top of the radio set…programs have been satisfactorily transmitted and received over distances of 25 miles from the Empire State Building…."[12]

The Year 1939

The *New York Times* announced in January 1939 that "…NBC would begin a regular [television] program service and that the RCA Manufacturing Company would place television receiving sets on the market in April 1939…."[13] Thus, it was proclaimed that TV had arrived! Commercial programming, as shown in the program schedule of Fig. 8, officially began on July 1, 1941, when NBC's W2XBS became WNBT.[14]

The 12-inch picture tube of the RCA TRK-12 that was put on the market (see Fig. 7) displayed a 'black and white' image composed of 441 lines, interlaced at 30 frames per second. This was the newly adopted RMA standard. RCA wisely included a radio receiver so that the rarely-used console could be enjoyed

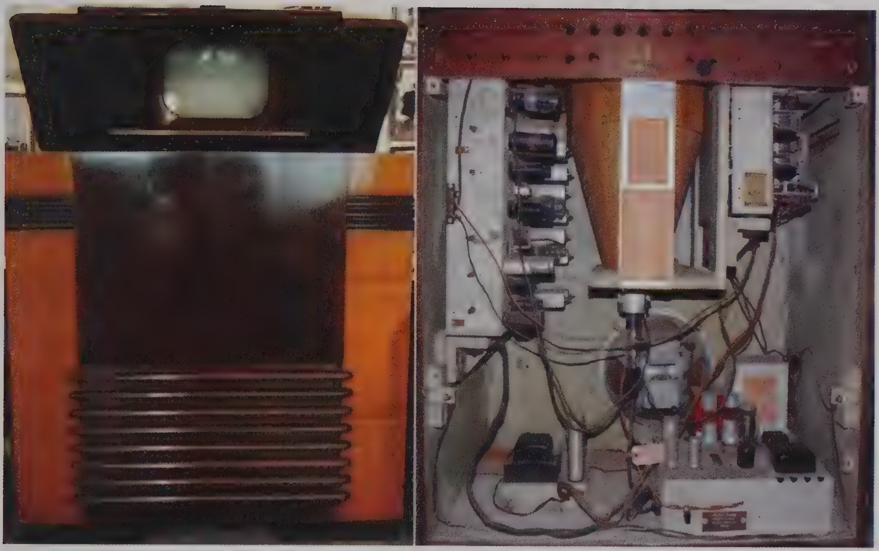


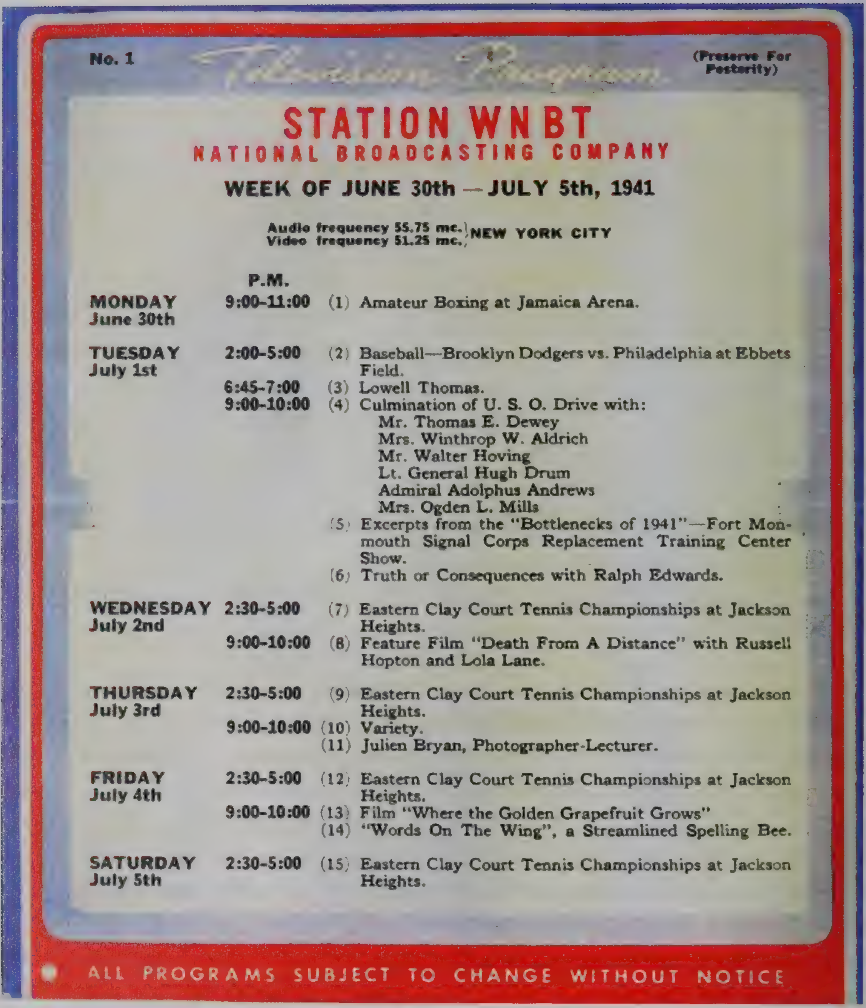
Fig. 7. RCA announced that NBC would begin a regular television program service and the RCA Manufacturing Company would place this RCA TRK-12 television receiving set on the market in April 1939. (R. Brewster)

when there were no TV transmissions. The assembly on the left of the rear view is the TV receiver system. The radio chassis is upper right. Immediately below is the TV power supply. The small chassis to the left is the radio power supply. Channel selection was from 1 to 5. Sound was AM, but the FM transmission could be received by "slope detection." There was no RF amplifier.

Postscript

It is interesting to compare the work of Zworykin to that of Philo Farnsworth, who had been developing a television system. Farnsworth established a short-term relationship with the Philco Corporation from 1931 to 1933, but Zworykin established a dedicated long-term employee relationship with RCA, where he rose up through the ranks and received many honors. Philco, at that time, was a very successful company, and certainly could have supported a serious television development program. But where RCA under David Sarnoff "pulled out all the stops" to develop TV, Philco gave up.

Note: The postscript is intended to show that RCA made a very serious (expensive) effort to develop a workable TV system…it is not obvious just how our TV system would have come about…government efforts? So it seems to me that Farnsworth (some think he "invented" television) could have been instrumental in developing TV by working with Philco.



No. 1 Television Program (Preserve For Posterity)

STATION WNBT

NATIONAL BROADCASTING COMPANY

WEEK OF JUNE 30th — JULY 5th, 1941

Audio frequency 55.75 mc.
Video frequency 51.25 mc. NEW YORK CITY

	P.M.		
MONDAY June 30th	9:00-11:00	(1)	Amateur Boxing at Jamaica Arena.
TUESDAY July 1st	2:00-5:00	(2)	Baseball—Brooklyn Dodgers vs. Philadelphia at Ebbets Field.
	6:45-7:00	(3)	Lowell Thomas.
	9:00-10:00	(4)	Culmination of U. S. O. Drive with: Mr. Thomas E. Dewey Mrs. Winthrop W. Aldrich Mr. Walter Hoving Lt. General Hugh Drum Admiral Adolphus Andrews Mrs. Ogden L. Mills
		(5)	Excerpts from the "Bottlenecks of 1941"—Fort Monmouth Signal Corps Replacement Training Center Show.
		(6)	Truth or Consequences with Ralph Edwards.
WEDNESDAY July 2nd	2:30-5:00	(7)	Eastern Clay Court Tennis Championships at Jackson Heights.
	9:00-10:00	(8)	Feature Film "Death From A Distance" with Russell Hopton and Lola Lane.
THURSDAY July 3rd	2:30-5:00	(9)	Eastern Clay Court Tennis Championships at Jackson Heights.
	9:00-10:00	(10)	Variety.
		(11)	Julien Bryan, Photographer-Lecturer.
FRIDAY July 4th	2:30-5:00	(12)	Eastern Clay Court Tennis Championships at Jackson Heights.
	9:00-10:00	(13)	Film "Where the Golden Grapefruit Grows"
		(14)	"Words On The Wing", a Streamlined Spelling Bee.
SATURDAY July 5th	2:30-5:00	(15)	Eastern Clay Court Tennis Championships at Jackson Heights.

ALL PROGRAMS SUBJECT TO CHANGE WITHOUT NOTICE

Fig. 8. Television program schedule for the first official week of television broadcasting on WNBT, June 30 to July 5, 1941. Note the marking "Preserve For Posterity." (And so it has been preserved.) (Brewster collection from the pamphlet "Television Program")

Endnotes

1. "Television with Cathode-Ray Tube for Receiver," *Radio Engineering*, Dec. 1929, p. 38.
2. VKZ Report to W. A. Tolson at GE, GE internal document, Jan. 18, 1930.
3. Albert Abramson, *The History of Television, 1880 to 1941*, (McFarland & Co., Aug. 1987) p. 144.
4. Ross Kilgore, author's interview, June 3, 1989.
5. Harley Iams, "Wiring of the 1st cabinet Television Receiver," Oct. 10, 1929 (A. Abramson).
6. Albert Abramson, *The History of Television*, p. 180.
7. V. K. Zworykin, "Description of an Experimental Television System and the Kinescope," *Television*, Vol. I, (RCA Institutes Technical Press, July 1936) pp. 149–150.
8. The use of electronic sync generators required

that the number of lines be multiples of small odd integers in order to interlock the line and frame frequencies; thus 243 lines = 9 × 9 × 3 and 343 lines = 7 × 7 × 7. The eventual line numbers of 441 and 525 were similarly chosen.

9. "Description of Television Apparatus Used for Demonstrations during February 1933," RCA Victor Company, Inc. Research Division report *TR-208C*, May 24, 1933 (Hagley Museum and Library, Wilmington, DE).
10. R. S. Holmes "Development of a Low Priced Television Receiver," RCA Victor Company, Inc. Research Division report *TR-244-C*, Nov. 9, 1934, stamped confidential when it was written on Sept. 9, 1934, and "no longer" on Apr. 15, 1937. (Hagley Museum and Library, Wilmington, DE)
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About the Author

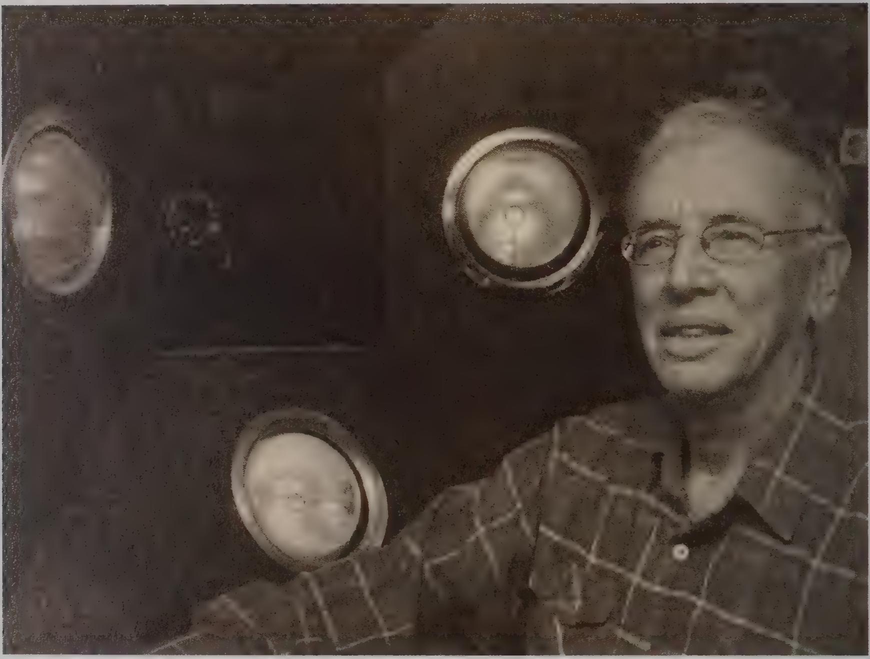
Richard Brewster became interested in all things electronic at about the age of ten. Initially, his activity was examination by disassembly, but it then turned into project building. After some failures, there was success in building a Heathkit phonograph. TV interest began when he and his brothers discovered a pre-war TV in an abandoned warehouse; he then turned it into an oscilloscope.

Richard graduated from Worcester Polytechnic Institute in 1960, receiving a bachelor's degree in Electrical Engineering. His first job assignment was designing a multi-band submarine radio direction finder, at a time when the choice for active elements was between nuvistors and transistors. Later he worked on specialized navigation equipment for the Air Force and Navy. Finally, he settled on a long-term position with Westinghouse as designer of nuclear electrical and control systems. He also supervised the construction and startup of nuclear power stations in the United States and overseas. At Westinghouse's Pittsburgh headquarters, he was involved with the famous radio station KDKA and the founding of the Pittsburgh Antique Radio Society. This rekindled his original interest: television. In the late 1970s, he acquired another pre-war TV, this one a basket case, which became a successful restoration project. Years later, an RCA TRK-12 was also brought back to life.

Richard ended his fun with Westinghouse in 1995 and became the *AWA Journal* TV column author and editor. He sought out and interviewed significant people in the history of TV development, which became material for his column. A 2012 story on Hollis Baird's TV work led to him receiving the *Bruce Kelley OTB Award.*

Amongst all these career moves, Richard married, had three daughters, several grandchildren, and now three great-grandchildren! He spends a large part of his retirement involved with the NGO *Mercy Ships*, and in 2000 held the position of Chief Radio Officer on a 12,000-ton hospital ship. This, without a ham radio license! (And to this day he still does not have a ham license!) Since much equipment on the ship was vintage, tracking down problems is always interesting. He was able to bring the ship's gyrocompass back to life. He has also repaired several nearby docked ships' communications systems. More recently, Richard volunteered as a surgical photographer for *Smile Train*, the cleft-lip palate repair group that repairs faces in West Africa.

Brewster most recently was a 'volunteer' Project Engineer during the early stages of construction of Mercy Ships' latest ship, the 37,000-ton *Global Mercy*. He and Susan spent two years traveling back and forth to Tianjin, China. The ship is now complete and in medical service in West Africa.



Richard Brewster

Transmission Line Loudspeakers: A Perspective

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Loudspeakers are important to maintain fidelity of sound in radios, TV, and theater. The perception of sound is personal. The reproduction quality of different kinds of loudspeakers and the electronics has been debated by aficionados, for decades. This review is for a class of loudspeakers categorized as transmission line (TL) loudspeakers. The first TL loudspeaker was described by Benjamin Olney from Stromberg-Carlson, a Rochester, NY, company, in a patent in 1936. This was a labyrinth speaker which can be classified as the first TL loudspeaker. The goal in the early loudspeakers was to modify and suppress acoustic radiation from the rear of the speaker-driver so that there was an improvement in bass. Further work on such speakers concentrated on materials that could suppress selective radiation from the rear diaphragm. However, in 1984, a class of loudspeakers was introduced by Bose, labeled acoustic wave speakers. Rather than suppressing the radiation from the rear of the driver, a means was provided, using standing waves, to take advantage of radiation from both the front and rear of the driver and sum them constructively. This allowed for a very good bass response in a small volume. The science and operation of TL speakers is the subject of this review. Analogs between acoustic transmission lines and electromagnetic transmission lines will be described. Also, analogies between antennas and the acoustic wave system will be mentioned.

Introduction

Listening to sound has always been and will continue to be a subjective experience. In audio, there has been a cult following that has debated the properties of various types of loudspeakers and amplifiers. The faithful reproduction of bass has been important to those who listen to music and those who view TV and movies. Reproduction of sound in a home environment is different from sound in a movie theater where special effects may require enhancement of bass. Homes usually have limited space and it is important to maintain a faithful reproduction of sound in small rooms for communal listening.

I started tinkering with loudspeakers in India during the 1960s to faithfully reproduce the sounds of recorded music. I experimented with both closed box and ported speakers. The quality of drivers available in the 1960s was unsatisfactory and created significant distortion. Furthermore, there were unwanted resonances in ported speakers. To create a satisfactory bass response, the drivers had to be large, which required large enclosures. A family friend owned a Stromberg-Carlson 145-L that I repaired occasionally by replacing vacuum tubes and other components.

I revisited the fidelity of low-frequency sounds while designing medical-doppler ultrasound systems during the early 1980s. I worked at Bose to understand acoustics and was fortunate to be the engineering manager of the group that introduced the Acoustic Wave Music System (AWMS) in 1984.

I have been studying architectures of various loudspeakers. TL loudspeakers have always interested me because of analogies between electromagnetic transmissions, acoustic wave systems, optical double-slit systems, and microwave waveguides.[1]

This review is a historical journey starting with the works of Olney and culminating with the Bose system and its variants.[2] Analogs between transmission line matching in microwaves, TL speakers, and the AWMS will be described, both qualitatively and quantitatively.

Early Work

It is well known that the low-frequency response of an unenclosed speaker-driver is limited due to cancellation of sound waves emanating from the front and back of the speaker. These waves are 180 degrees out of phase with each other, which results in destructive interference, particularly at low frequencies. Low frequencies are omnidirectional, unlike higher frequencies that are directional. The speed of sound is 343 m/s (1125 ft/s), and 100 Hz represents 3.43 m (11.25 ft), so a 4 inch loudspeaker driver is relatively small. Therefore, there is almost a complete cancellation at low frequencies of radiation between the front and back of the diaphragm. Closed box and ported speakers are designed to alleviate this problem by restraining radiation on one side of the driver and shifting the phase from the other side of the driver to add them constructively. To obtain an adequate sound pressure level (SPL), these speakers and the drivers had to be large. Helmholtz resonance and port noise had to be managed in ported speakers. Small ports created audible noise, due to turbulence and flow separation at the ports.

Conceptually, an infinite baffle was postulated (Fig. 1) where radiation took place from only one side of the driver with suppression of radiation from the other side. This concept is analogous to an isotropic radiator in antennas. This concept has been used with large baffles with large path lengths between the front and back radiating surfaces.

A variation of the infinite baffle is the infinitely long cylinder to suppress radiation from the rear of the driver. A driver is mounted to an infinitely long cylinder with suppression of radiation from the back of the driver. The goal of early TL

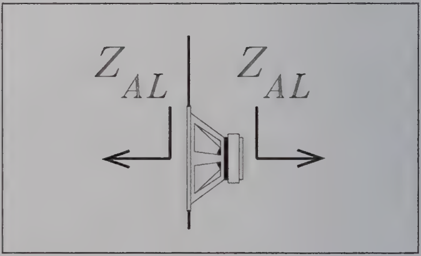


Fig. 1. Conceptualized infinite baffle. (Robinson, p. 32)

speakers was to suppress unwanted radiation from the back of the driver.

Stromberg-Carlson was a telephone and radio manufacturing company situated in Rochester, NY, on Carlson Road (Fig. 2) that manufactured radio receivers and consoles. Olney disclosed an acoustic labyrinth speaker in his 1936 patent which was assigned to Stromberg-Carlson (see Fig. 3).[3] The walls of this speaker were lined with sound-absorbing materials to obviate the need to have an infinite cylinder. Olney used acoustic analysis and trial and error in designing his system. Qualitatively, he used a long duct with a path length such that at a low frequency the sinusoidal radiation of bass emanating from the back of the driver was inverted and then summed with radiation emanating from the front of the driver. Higher frequencies were eliminated by using a lossy lining in the cabinet. All TL speakers are based on this principle. TL speakers, until the advent of the Bose AWMS, dissipated

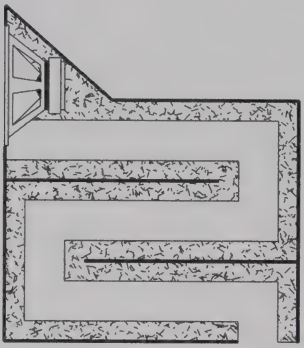


Fig. 3. Olney's labyrinth. (Robinson, p. 2)

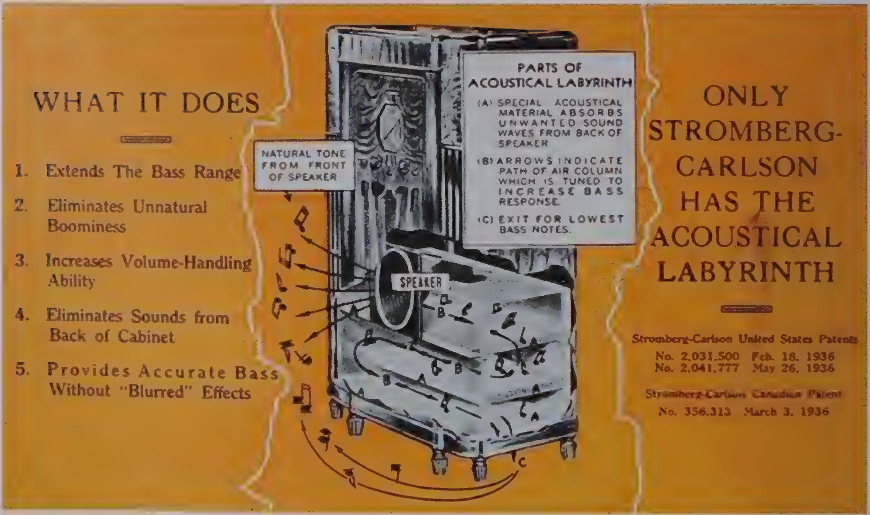
Fig. 2. Stromberg-Carlson Radio and Telephone Manufacturing Company, Carlson Rd, Rochester, NY. (Stock photo, Stromberg-Carlson sales brochure, 1929)

energy from the rear of the driver. Furthermore, these speakers required a large acoustic path length. In his patent, Amar Bose refers to the teachings of Olney during the development of the AWMS.[4]

Stromberg-Carlson manufactured the model 145-L with a labyrinth. This was a 10-tube console radio, the acoustical labyrinth of which is shown in Fig. 4. An advertisement for the model 140-L radio with the same acoustical labyrinth is shown in Fig. 5. The model 145-L view from the rear, shows portions of the labyrinth that can be seen externally (see Fig. 6).

In 1965, A. R. Bailey described a non-resonant cabinet. He eliminated resonances in bass-reflex cabinets rather than open-backed cabinets.[5] Sound persisted for a time when such speakers were subjected to an impulse response due to lack of damping and resonant effects in the speaker. His solution was a speaker filled with damping material rather than using lined material as in Olney's speaker. This solution was a folded acoustical transmission line filled with damping material. He found that long-fibered wool was most effective as damping material. The end of the folded tube was in the same plane as the driver. At lower frequencies, both the driver and the end of the folded tube were in phase, thereby amplifying the lower frequencies, whereas the higher frequencies were damped by the woolly filling. His construction techniques were heuristic. Fig. 7 illustrates a production version of Bailey's speaker.

L.J.S. Bradbury in 1976 investigated the properties of long-fibered wool as packing material.[6] His investigations showed that for a packing density of 8 kg/m³, frequencies greater than 100 Hz were greatly attenuated. Furthermore, if the



WHAT IT DOES

1. Extends The Bass Range
2. Eliminates Unnatural Boominess
3. Increases Volume-Handling Ability
4. Eliminates Sounds from Back of Cabinet
5. Provides Accurate Bass Without "Blurred" Effects

NATURAL TONE FROM FRONT OF SPEAKER

PARTS OF ACOUSTICAL LABYRINTH

(A) SPECIAL ACOUSTICAL MATERIAL ABSORBS UNWANTED SOUND WAVES FROM BACK OF SPEAKER

(B) ARROWS INDICATE PATH OF AIR COLUMN WHICH IS TUNED TO INCREASE BASS RESPONSE.

(C) EXIT FOR LOWEST BASS NOTES.

ONLY STROMBERG-CARLSON HAS THE ACOUSTICAL LABYRINTH

Stromberg-Carlson United States Patents

No. 2,031,500 Feb. 18, 1936
No. 2,041,777 May 26, 1936

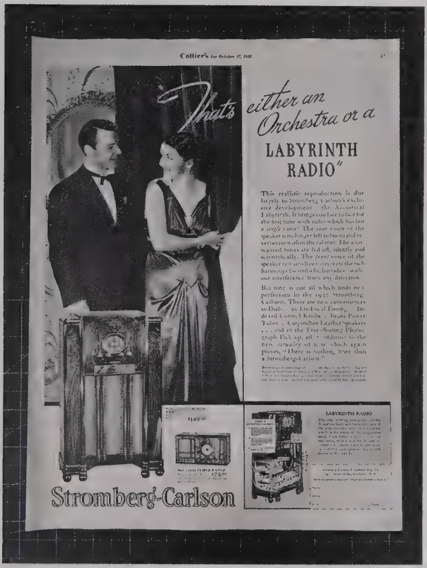
Stromberg-Carlson Canadian Patent

No. 356,313 March 3, 1936

Fig. 4. Stromberg-Carlson acoustical labyrinth, such as used in the model 145-L 10-tube radio. This same acoustical labyrinth was used in other models of a similar size. (*Stromberg-Carlson* sales brochure, 1936)

length of the tube was half a wavelength, the sound from the front diaphragm and the port added constructively.

Bose introduced the Acoustic Wave Music System in 1984, which eliminated the filling material in the transmission lines.[7] The analysis of this system is complex and will be dealt with later in this paper. The front waveguide is one-third the length of the rear waveguide with the



Collier's for October 17, 1936

That's either an Orchestra or a LABYRINTH RADIO"

Stromberg-Carlson

Fig. 5. Ad for a Stromberg-Carlson radio using the acoustical labyrinth. (*Collier's* Oct. 17, 1936)

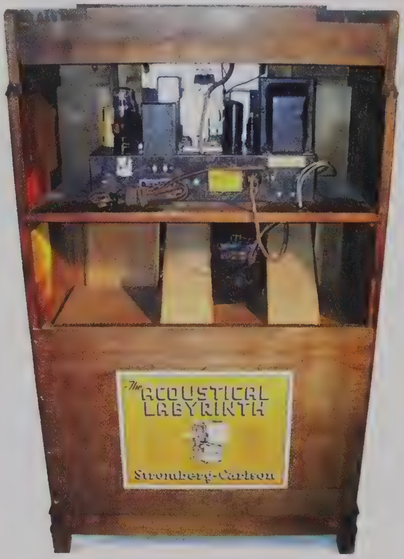


Fig. 6. Stromberg-Carlson model 145-L from the rear, showing portions of the labyrinth that can be seen externally. (https://www.radio-antiks.com/IndexRadio-Antiks_StrombergCarlson_145L.htm)

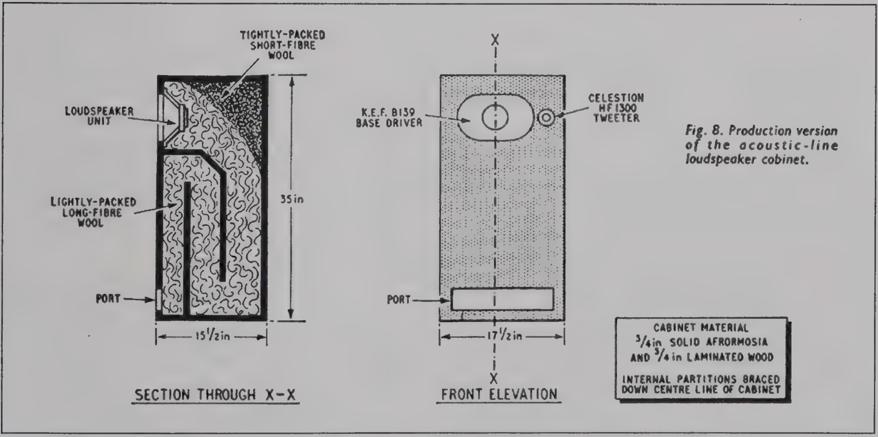

TIGHTLY-PACKED SHORT-FIBRE WOOL
LOUDSPEAKER UNIT
LIGHTLY-PACKED LONG-FIBRE WOOL
35in
PORT
15½in
SECTION THROUGH X–X
X
K.E.F. B139 BASE DRIVER
CELESTION HF1300 TWEETER
PORT
17½in
X
FRONT ELEVATION
Fig. 8. Production version of the acoustic-line loudspeaker cabinet.
CABINET MATERIAL ¾in SOLID AFRORMOSIA AND ¾in LAMINATED WOOD
INTERNAL PARTITIONS BRACED DOWN CENTRE LINE OF CABINET

Fig. 7. Production version of Bailey's speaker. (*Wireless World*, Oct. 1965)

total length in the folded configuration of 7 feet. This allowed bass reproduction down to 50 Hz in a small volume, as shown in the cutaway view of Fig. 8. Variants of this system are the popular Bose radio and the Acoustic Cannon.

In this review, I will delve into both qualitative as well as quantitative understanding of transmission line loudspeakers. Circuit and transmission line analogies will be used copiously to illustrate basic concepts.[8]

Analysis and Modeling

To explain the operation of TL speakers, a few theoretical foundations will be defined. This will help with both a qualitative and quantitative understanding. In this review, I will stay with essentials without indulging in details of theoretical acoustics. Several master's and doctoral theses have been devoted to the analysis and design of various transmission line speakers. A great deal of work has been done in these areas (see endnotes and other sources). I will concentrate on low-frequency response where sound is omnidirectional. Analogies between electrical transmission lines and waveguides will be highlighted. A knowledge of phasors is useful but not necessary to understand the concepts, especially for those who are familiar with antennas and transmission line matching. Concepts from circuit theory and transmission lines will be used to illustrate the operation of these loudspeakers. The goal in all systems is maximum power transfer from the generator to the radiator. The acoustic generator is a speaker driver.

Systems, both electromagnetic and acoustic, require the generation of energy. A speaker driver generates acoustic energy, which ultimately reaches the ear. These can be divided into three domains: electrical, mechanical, and acoustic. Both mobility and impedance circuit models will be used in the descriptions. In impedance analog circuits, voltage is analogous to mechanical force and acoustic pressure. Current is analogous to mechanical velocity and acoustical volume velocity. In a mobility circuit model analog, voltage is analogous to mechanical velocity.[9] Current is analogous to mechanical force and acoustic pressure. Both these analogs are duals of each other.

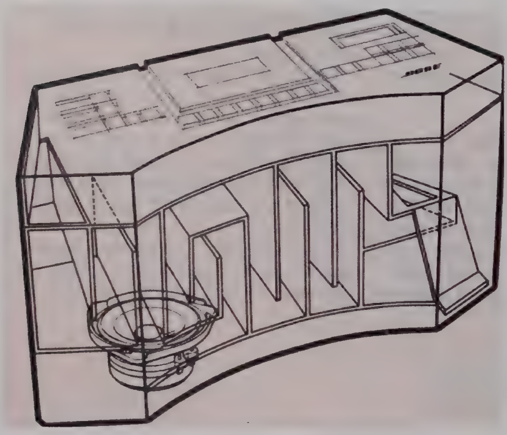


Fig. 8. Cutaway of the Bose Acoustic Wave Music System. (*Audio*, Nov. 1991, p. 31)

Fig. 9 depicts a schematic of a loudspeaker driver. The electrical domain is characterized by a voice coil with a DC resistance and inductance. In actual speakers, the inductance is variable

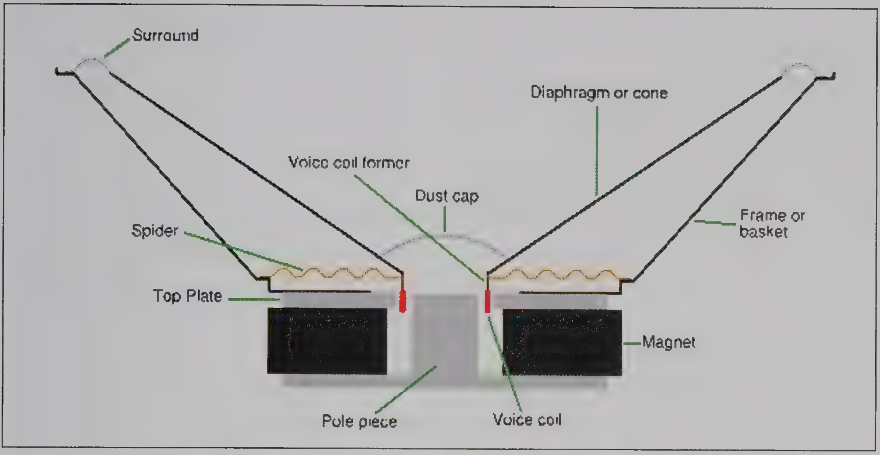


Fig. 9. Depiction of a loudspeaker driver. (http://mh-audio.nl/Loudspeaker.html)

and frequency dependent and can contribute to distortion. The mechanical domain is characterized by mass of the diaphragm, compliance of the suspension, and mechanical damping. The acoustical domain is characterized by acoustic impedances: Z_{AF}, at the forward of the diaphragm, and Z_{BF}, behind the diaphragm. The speaker is mounted in an enclosure and therefore compliance is defined, corresponding to the volume of air.

Works of several researchers have influenced the following models (see endnotes and references). Phasor notation is used but is not necessary for qualitative understanding, during the rest of this review.

Electrical Circuit of a Speaker

Loudspeaker drivers are characterized by Thiele/Small parameters that are used in electrical modeling of drivers (see Fig. 10).[10] Each driver is characterized by the parameters shown in Table 1.

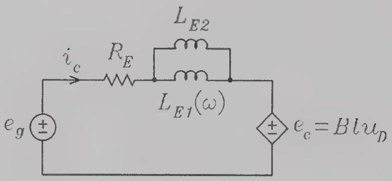


Fig. 10. Impedance model of a loudspeaker driver. (Robinson, p. 24)

Table 1. Thiele/Small parameters used to define low-frequency performance of a loudspeaker.

Thiele-Small parameters	
Symbol	Parameter
R_e	DC resistance of voice coil
L_e	Self-inductance of voice coil
Bl	Force factor
M_{md}	Mass of diaphragm
C_{ms}	Compliance of suspension
R_{ms}	Mechanical damping
f_s	Resonance frequency
Q_{ms}	Mechanical quality factor
Q_{es}	Electrical quality factor
Q_{ts}	Total quality factor
S_d	Area of diaphragm
V_{as}	Equivalent volume

Voltage e_g depicts a voltage source which is the amplifier. The symbol i_c depicts the voice coil current. Symbol L_{E2} depicts a fixed inductor and symbol $L_{E1}(\omega)$ depicts a frequency-dependent inductor. Blu_D is the back-emf generated as the voice coil moves in and out of the magnetic field. The inductances can change due to changes in flux linkages as the voice coil moves in and out of the magnetic field. These nonlinear effects contribute to distortion in loudspeakers. The force developed by a voice coil is BLi_c, where B is flux density and L is length of the coil.

Mechanical Circuit

Mechanical elements of a speaker can be modeled as shown in Fig. 11. Mass (a) is analogous to inductance, compliance (b) is analogous to capacitance, and resistance (c) is analogous to electrical resistance, using impedance models. Some authors use mobility models wherein (a) is analogous to compliance, (b) is analogous to inductance, and (c) is analogous to electrical resistance. Both these models are equivalent, using the principle of electrical duality.

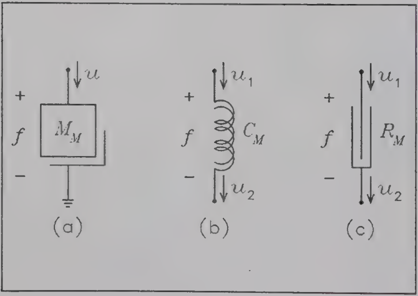


Fig. 11. Mechanical elements: (a) Mass (b) Compliance (c) Resistance. (Robinson, p. 16)

When force F is applied to a mechanical mass M_M, it causes it to accelerate in accordance with the equation $F = M_M(du/dt)$ or in phasor notation, for a sinusoidal excitation, $F = j\omega M_M u$, where ω is the angular frequency of excitation and $j = (-1)^{1/2}$ which is an imaginary number. (If a sinusoidal voltage V is applied, to elicit a current i and the inductance is L, then $V = j\omega Li$.) Hence the mass M_M is an analog of the inductance L.

Mechanical compliance occurs when force is applied to a spring per $F = (1/j\omega C_M)V$, where C_M is an analog of a capacitance, F is analogous to current, and V is analogous to voltage applied to the capacitor.

Losses are modeled using a mechanical resistance R_M. This resistance can include the loss in a filled transmission line as well as other mechanical losses.

Acoustical Circuit

Consider a cylinder of length l, with a diameter of S, subjected to a differential pressure p. If u is velocity, then pressure p is related to the volume velocity U by: $p = (\rho l/S)(dU/dt)$, where the density of air expressed as ρ. In phasor notation, $p = j\omega M_a U$, where M_a is the acoustical mass. The acoustical mass, therefore, is an analog to an inductor. Similarly, it can be shown that acoustic compliance is an analog to a capacitor. Acoustical resistance is an analog to a resistor and is both due to flow in a tube as well as losses through fibrous material. Particularly, with lossy fibrous material the resistance can be nonlinear. The effective speed of sound can vary due to the presence of this material.

Analogies

Some equations are mentioned below illustrating analogies to quantitatively describe TL and acoustic wave loudspeakers. These equations are not required for a qualitative understanding.

Electromagnetic waves and acoustic waves are characterized by the Helmholtz equations. In electromagnetics, it is the speed of light that governs transmission, and in acoustics, it is the speed of sound. For a plane acoustic wave, such as in a cylinder with a piston at one end (see Fig. 12), we have the following reduced equation:

$$d^2p(z)/dz^2 + k^2p(z) = 0, \qquad \text{eq. (1)}$$

where $k = \omega/c$, c is the speed of sound, and ω is the radian frequency. This equation is a familiar equation in electromagnetics where c is the speed of light.

A lumped parameter model for a lossy electromagnetic line is illustrated in Fig. 13. It can be shown that the characteristic electrical impedance of the line is:

$$Z_0 = (R + j\omega L)/\gamma = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}} \qquad \text{eq. (2)}$$

And for an acoustic transmission line:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}, \text{eq. (3)}$$

In Fig. 13, replace the inductance with $m_{aa}\Delta z$, where m_{aa} is the acoustical mass per unit length; the capacitance with $c_{aa}\Delta z$, where c_{aa} is the acoustic compliance per unit length; and the resistance with $r_{aa}\Delta z$, where r_{aa} is the acoustic resistance per unit length. $G\Delta z$ is zero as there is no acoustic conductance. Symbol p is pressure and U is the volume velocity, which is the particle velocity of air u multiplied by the area of the tube.

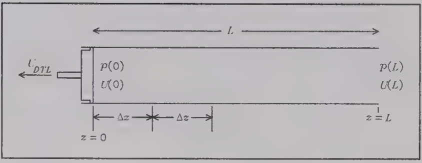


Fig. 12. Transmission line with a piston at one end. (Robinson, p. 53)

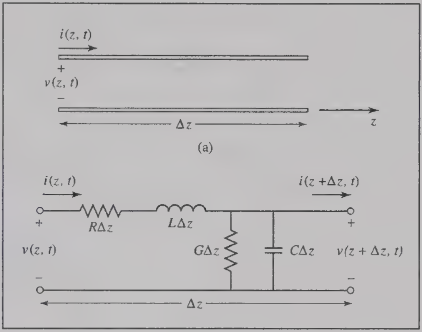


Fig. 13. Lossy lumped model of an electromagnetic transmission line. (Pozar, *Microwave Engineering*, p. 49)

The solution for this equation is familiar in transmission line theory. The solution for pressure is given by:

$$p(z) = p_{0+}e^{-\Upsilon z} + p_{0-}e^{+\Upsilon z}, \qquad \text{eq. (4)}$$

where p_{0+} is the amplitude of a wave traveling in the $+z$ direction, and p_{0-} is the corresponding wave in the $-z$ direction.

The particle velocity is obtained as:

$$u(z) = (1/\rho_0 c)(u_{0+}e^{-\Upsilon z} - u_{0-}e^{+\Upsilon z}), \qquad \text{eq. (5)}$$

where ρ_0 is air density.

The above equations are the familiar forward and backward waves in a transmission line, where voltage is analogous to pressure and current is analogous to particle velocity.

If the tube is infinitely long, we have the familiar equation for characteristic acoustic impedance:

$$Z_C = \rho_0 c/S_T, \text{ or } \sqrt{(m_{aa}/c_{aa})},$$

where S_T is the cross-sectional tube area for a lossless tube, ρ_0 is air density, and c is the speed of sound.

For a lossy tube, the characteristic impedance is

$$Z_C = \sqrt{((r_{aa} + j\omega m_{aa})/j\omega c_{aa})}.$$

At the end of the lossless tube, the acoustic impedance is given by:

$$Z_{AL} = p(L_T)/U(L_T), \qquad \text{(eq. 6)}$$

$$\text{or} = (\rho_0 c/S_T) \times \frac{(p_{0+}e^{-jkL}{}_T + p_{0-}e^{+jkL}{}_T)}{(p_{0+}e^{-jkL}{}_T - p_{0-}e^{+jkL}{}_T)}.$$

The input impedance is given by:

$$Z_{AT} = (\rho_0 c/S_T) \times \frac{(Z_{AL} + j(\rho_0 c/S_T)\tan(kL_T))}{((\rho_0 c/S_T) + jZ_{AL}\tan(kL_T))}$$

$$\text{or } Z_{AT} = Z_C \times \frac{(Z_{AL} + jZ_C \tan(kL_T))}{(Z_C + jZ_{AL}\tan(kL_T))}, \qquad \text{(eq. 7)}$$

where $Z_{AT} = p(0)/U(0)$.

In Fig. 14, the model for bass loading is $M_{A1} = (0.61\rho_0)/(\pi a_D)$, where a_D is the radius of the diaphragm. Fig. 15 illustrates the normalized behavior of a transmission line.

In the following pages, TL speakers are described both analytically as well as intuitively. Wherever, possible, historical explanations have been preserved. Serious researchers as well as audio aficionados have written articles and theses about TL speakers. Many of these works are either intractable due to mathematical complexities or hand-waving arguments about transmission line speakers.

I divide TL loudspeakers into two categories: dissipative and non-dissipative. Dissipative speakers are those where energy is deliberately dissipated from the rear of the diaphragm as in labyrinth speakers. I define non-dissipative speakers as those that use the energy from the rear of the diaphragm to enhance low-frequency performance, without use of fillers at the rear of the diaphragm. Of course, there are energy losses such as resistance to flow as well as electrical resistance.

Unified Explanation of Dissipative and Non-Dissipative Loudspeakers

The approach, in this review, uses the illustration in Fig. 15 to explain the operation of both kinds of loudspeakers. At low frequencies in the model, illustrated in Fig. 14, the transmission line is terminated by the inductor M_{A1}. Therefore, the inductive reactance is almost a short circuit. The response in Fig. 16 is appropriate to describe the behavior of TL loudspeakers.

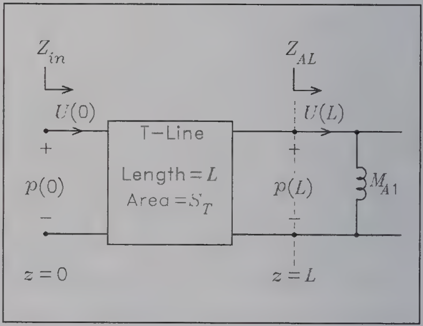


Fig. 14. Transmission line model for bass response. (Robinson, p. 59, modified)

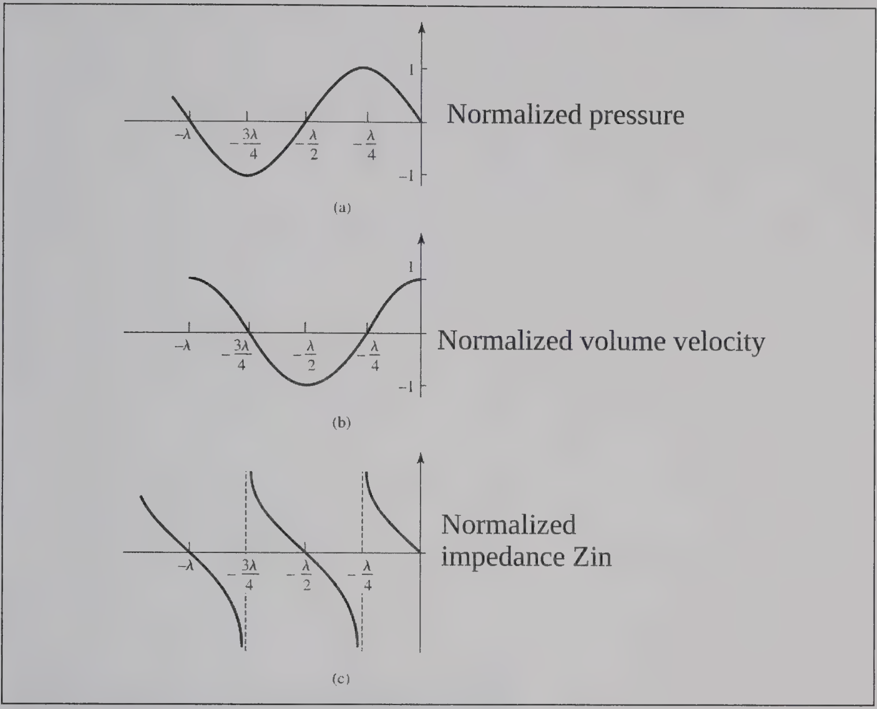


Fig. 15. Normalized behavior of short-circuited transmission line: (a) Pressure (b) Volume velocity (c) Impedance *Zin* (acoustic analogs). (Pozar, p. 60)

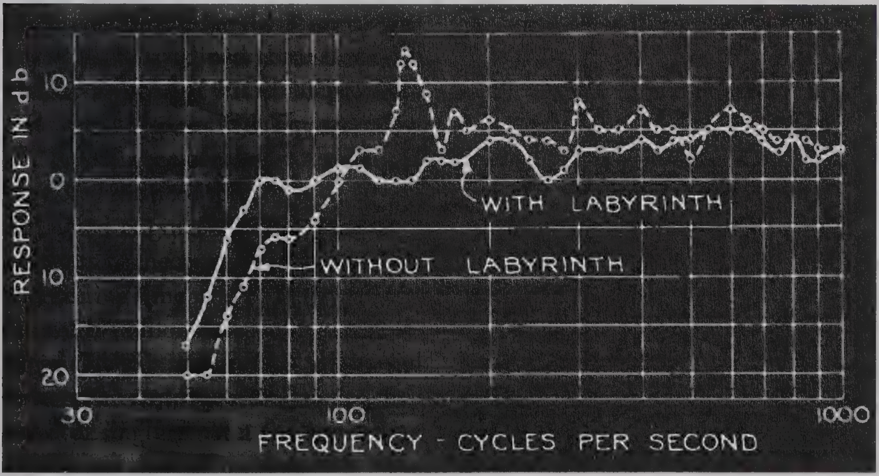


Fig. 4—Response of 8 in. cone loudspeaker in cabinet 2 ft. x 2 ft. x 1 ft. inside dimensions. Back of cabinet 2 in. from wall

Fig. 16. Frequency response of Olney's loudspeaker. (Olney, *Electronics*, 1937)

Dissipative or 'Labyrinth' Loudspeakers

Benjamin Olney, from Stromberg-Carlson, developed the first labyrinth loudspeaker during the early 1930s. Consider a tube of length ½λ. Assume that the output of the TL (tube) is the normalized volume velocity, +1 (Fig. 15(b)). The velocity at the head of the tube, or rear of the diaphragm, would be approximately -1. The acoustic impedance at the rear of the diaphragm, at ½λ, would be very small. It is never zero in an actual tube, due to factors such as resistive dissipation, as it takes energy to propel the wave. Here, λ is chosen to be the wavelength corresponding to 70 Hz. The waves from the front of the driver and the output of the tube are summed to enhance the bass. Higher frequencies are dissipated using lossy material in the rear and low pass filtering, using a crossover circuit, before the driver is energized.

In a dissipative speaker, the gain of the tube is almost one (unity). If a wave must be propelled to the output of the tube, the back of the diaphragm must generate the same volume velocity. This requires a large speaker driver with large excursions of the voice coil, adding to distortion. The TL in dissipative speakers can, therefore, be characterized as a half-wave, lossy acoustic transformer with unity inverted gain.

An approach to explanation of the losses in dissipative loudspeakers uses a simple concept. In equation (4) the exponent $e^{-\gamma z}$ can be decomposed as $e^{-\alpha}e^{-j\beta}$ where $e^{-\alpha}$ is the dissipative term that is frequency and time-dependent. Various factors such as length of the labyrinth, fillers, and higher frequencies contribute to this term. Often $e^{-\alpha}$ must be determined empirically from properties of the materials as well as their densities. The effect of $e^{-\alpha}$ is to attenuate both the forward as well as the backward wave in an acoustic transmission line.

Non-Dissipative or Acoustic Wave Loudspeakers

It was recognized by Amar Bose and William Short, Fig. 17, during the 1980s that to generate "big bass in a small box"

Fig. 17. William Short (l) and Amar Bose (r) with the Bose Acoustic Wave Music System. (https://www.communityadvocate.com/2021/06/03/bose-inventor-finds-his-viking-muse/)

with low distortion, there needed to be a different approach from the labyrinth speakers. Instead of dissipating energy from the rear of the driver, it was utilized in a different way by using standing waves.

In Fig. 15(b) and (c), the transmission line at –¼λ and –¾λ corresponds to a high impedance and low cone velocity. Consider two tubes, with the tube at the back of the driver being three times as large as the one in front of the driver. The total length of these tubes was chosen to be approximately 2 meters (6.5 ft). These tubes are transmission line transformers with the larger tube inverting the radiation from the back of the driver and the shorter tube, connected to the front of the driver, which does not invert the signal. The outputs of both these tubes are added together through two output ports. In the Bose system, the low-frequency response was approximately 50 Hz. Electronic equalization was used to flatten the response of this system, which will be discussed in greater detail later. The behavior of this system is analogous to two monopole resonant antennas, of unequal length, separated from each other to constructively add their radiation.

First Labyrinth Speaker

Benjamin Olney, from Stromberg-Carlson, a Rochester company, in his 1936 patent and paper (*Electronics*, April 1937), recognized the analogies between an electrical transmission line and an acoustic transmission line. Propagation through electrical cables was well known using the telegrapher's equation, which was used to predict behavior of Morse code in long cables. His loudspeaker was the first labyrinth speaker. His work was seminal with respect to improving performance vis-à-vis an open-backed loudspeaker cabinet.

Olney recognized, as explained above, that if the radiation from the back of the speaker diaphragm was inverted in a folded tube and then summed with the radiation from the front, particularly for low-frequencies, which resulted in an enhanced bass. Furthermore, this behavior persisted when the path length is an odd number of half wavelengths. Higher frequencies were suppressed by felt lining in the labyrinth. Olney did several experiments to determine the quality of the lining as well as diameter of the drivers.

The response of Olney's loudspeaker is illustrated in Fig. 16. He used an 8-inch driver for his experiments. The 3 dB frequency is shown to be around 70 Hz. At the speed of sound at 343 m/sec, the wavelength for 70 Hz is 4.9 meters (16 ft). The half wavelength would be approximately 2.5 meters or about 8 feet. The 145-L used a 10 inch driver which necessitated a large folded labyrinth.

Furthermore, to move a large volume of air, the driver had to undergo large excursions, contributing to distortion. The labyrinth, commercialized by Stromberg-Carlson as the 145-L, was a high-end radio that was priced at around $150 in 1936. Table 2 shows the specifications for the 145-L, which had an output of 20 watts.

The labyrinth can be viewed as having an acoustic transformer with an

Table 2. Stromberg-Carlson model 145-L, 10-tube LW/AM-BC/Police/SW superheterodyne console radio information.

Type	Stromberg-Carlson 145-L
Production year	1936–37
Cabinet	Multi-tone wood
Dial	Backlit 4-band rotary dial with vernier dial, under glass
Knobs	5 wooden knobs with engraved writings
Frequency range	X (LW): 145–370 kHz; A (BCB): 530–1700 kHz; B (Police): 1700–5600 kHz; C (SW): 5.6–18.0 MHz
Controls	Volume, tone-fidelity, stations (tuning), ranges (band select), off-on-bass
Tube line-up	6K7(RF), 6J7(Osc), 6A8(Mod), 2x6K7(IF), 6Q7(Dem), 2x6L6(Aud), 6E5(eye), 5Z3(Rect)
Speaker	10" field coil speaker in Acoustical Labyrinth
Size	26"W x 15"D (with knobs) x 44½"H
Weight	106 lbs.

inverting gain of unity, followed by a lossy acoustic filter to absorb high-frequency sounds. The properties of the felt lining were experimentally determined. Further work on TL loudspeakers was devoted to modeling behavior of these systems and examining properties of various fibrous filler materials.

Filler Materials

An unfilled duct or labyrinth is acoustically hard. Without any filling, pressure loss is directly proportional to the length of the duct and inversely proportional to area. This is analogous to resistance in an electrical circuit. The area of the duct must be large enough so that the ensuing flow of air is laminar.

Bradbury, in 1976, investigated the properties of long-fibered wool as filling material.[11] He observed that in addition to damping high frequencies, the speed of sound was retarded in such material, which would allow a decrease in the length of the labyrinth. This is an analog of loading a resonant antenna with an inductor.

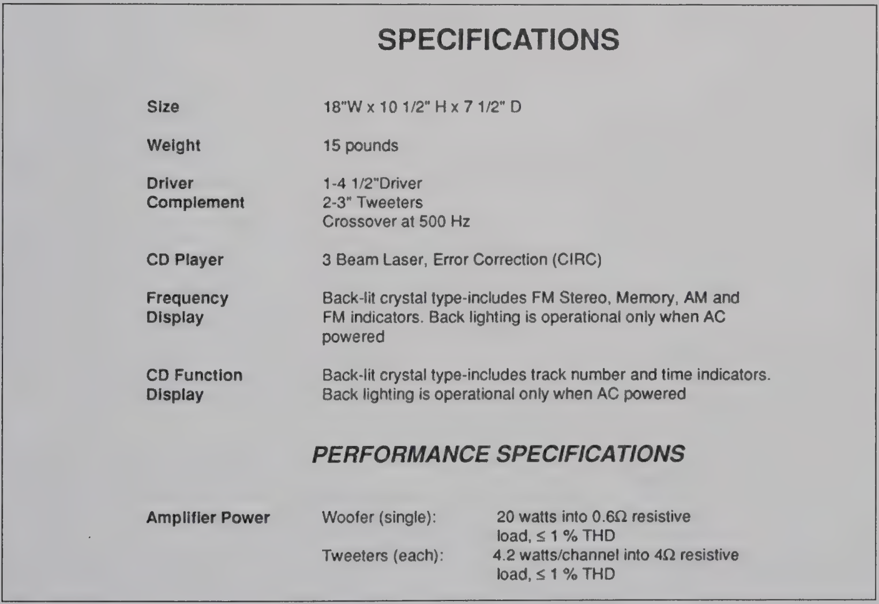
Airflow in a filled tube is complex. At low frequencies, the fibrous material oscillates like a mechanical low-pass filter. At higher frequencies, the flow is mainly due to porosity of the material, like flow in a sieve. The acoustic resistance of this sieve can be nonlinear with respect to pressure differences between both ends of the duct. The losses can be a function of the square of the velocity of the air. Packing density influences this behavior. The behavior is complex and is influenced by distortion of material due to flow. Please see the endnotes and references for researchers who tackled this problem. The *Journal of the Audio Engineering Society* has several papers devoted to damping in pipes.[12] Between hobbyists and serious researchers, a variety of filling materials has been studied. Filling materials have also been used in damping Helmholtz resonance in ported loudspeakers.

Fiberglass has also been used as packing material. Fiberglass is environmentally inert compared to organic material. Its properties are stable with temperature and humidity. Robinson devoted his doctoral dissertation to exploring the properties of fiberglass for various loudspeakers.[13]

Acoustic Wave Music System

Amar Bose and William Short in their 1986 U.S. Patent 4,628,528, described an acoustic wave system that is non-dissipative.[14] Bose refers to teachings by Olney in inventing a system that has the advantage of "Big Bass in a small box." The original AWMS had an FM/AM tuner and a cassette deck. Its successor had a CD player. The Bose radio is a smaller version of the original AWMS, which does not look to have the shape of the Watergate Complex (Amar Bose was rankled with this comparison).

Fig. 18 gives the critical sound specifications for the Bose CD2000 system. Fig. 19 illustrates the block diagram for



SPECIFICATIONS

Size	18"W x 10 1/2" H x 7 1/2" D	
Weight	15 pounds	
Driver Complement	1-4 1/2"Driver 2-3" Tweeters Crossover at 500 Hz	
CD Player	3 Beam Laser, Error Correction (CIRC)	
Frequency Display	Back-lit crystal type-includes FM Stereo, Memory, AM and FM indicators. Back lighting is operational only when AC powered	
CD Function Display	Back-lit crystal type-includes track number and time indicators. Back lighting is operational only when AC powered	

PERFORMANCE SPECIFICATIONS

Amplifier Power	Woofer (single):	20 watts into 0.6Ω resistive load, ≤ 1 % THD
	Tweeters (each):	4.2 watts/channel into 4Ω resistive load, ≤ 1 % THD

Fig. 18. Critical sound specifications for the Bose CD2000 system. (*Acoustic Wave Music System CD2000 Service manual*)

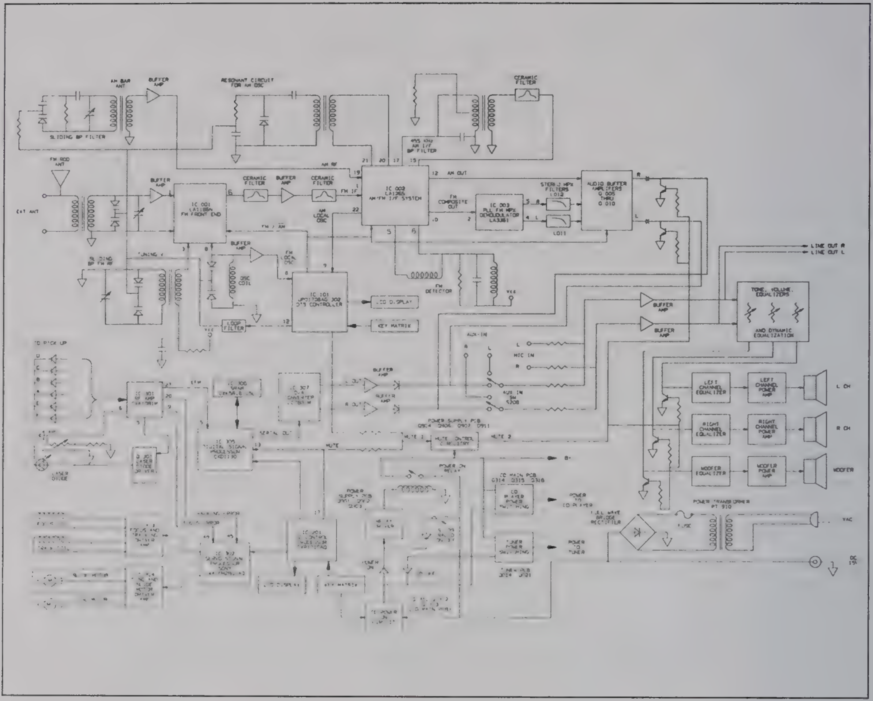


Fig. 19. Block diagram of the Acoustic Wave Music System. (*Acoustic Wave Music System CD2000 Service manual*)

this model. I described details of the Bose AWMS, both with reference to the patent as well as my observations while working at Bose.

The fundamentals of this system have been described earlier with reference to Fig. 15. The inspiration for this system was transmission lines used in RF and microwave systems.[15] Microwave systems regularly use quarter-wave transformers for impedance matching. The lower velocity at the speaker diaphragm is driven by a higher pressure (Fig. 15(a)), which is responsible for smaller coil motion. The power output is proportional to the product of pressure and volume velocity. At the end of the tube, the velocity is large and the pressure is small with the product of the velocity and pressure being slightly lower than that at the cone to account for losses in the tube. The tube must be large enough to maintain laminar flow. Pressure exerted on the walls of the tube can create vibrations, and if the tube is relatively stiff, the resultant noise will be negligible.

Radio engineers may view the AWMS as an analog to two monopole antennas, with different resonant frequencies. In one instance we deal with the speed of sound and in another instance, the speed of light. An optical analog is with Young's double slit experiment.

Standing acoustic waves have been used advantageously in the AWMS to recover energy from the rear of the diaphragm, which is otherwise dissipated in labyrinth speakers. Acoustic matching is common in musical instruments or organ pipes. A small breath of air creates a large sound that can fill a hall. However, only one frequency and its harmonics are matched, per pipe. Some of the distinguishing features of the AWMS vis-à-vis a labyrinth system are captured in Table 3.

Actual gain is smaller than theoretically predicted, due to flow losses in the acoustic path length. Electronic equalization is used to flatten the outputs so that they do not deviate more than 1 dB in the frequency of interest. The longer tube had a length of 1.4 meters (4.6 ft) in the patent disclosure, corresponding to a cutoff frequency of 60 Hz. The production system had an overall summed tube length of about 7 feet, corresponding to a lower cutoff frequency of about 50 Hz. The notch filter described in the patent was used to decrease the response below 40 Hz while maintaining the lower cutoff frequency at 50 Hz. The distance between woofer ports is about one-eighth the length of the larger waveguide, which manages the null that occurs when the output of the front and rear ports are summed. According to the patent, making this distance larger would decrease the system response at low- and midrange frequencies. Fig. 20 illustrates the equalization curve for the production system.

Table 3. Labyrinth/TL vs. AWMS distinguishing features.

Attribute	Labyrinth/TL	AWMS
Energy loss due to fillers/lining	Necessary	Reclaimed energy using standing waves
Distortion	High, due to excessive cone movement	Low, as cone moves into a high impedance followed by transformer gain
Tube gain	Unity	Can be very large due to transformer gain
Size of cavity	Large, due to unity transformer gain and necessity of moving a lot of air volume	Small
Driver diameter	10 inches	4.5 inches
Filler stability	Variable with environment and age	NA

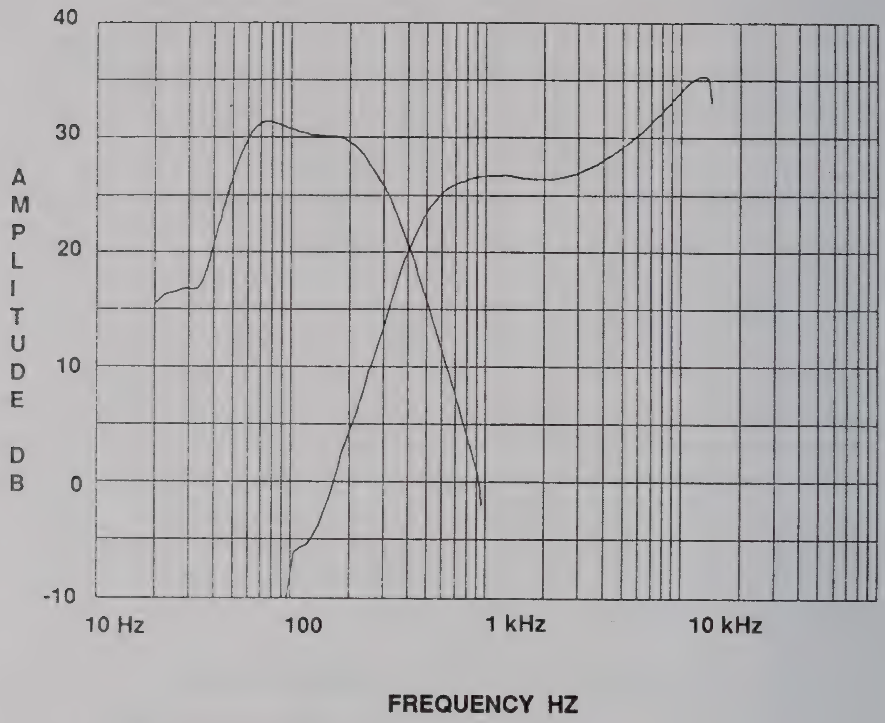


Fig. 20. Equalization curve for the production system. (*Acoustic Wave Music System CD2000 Service Manual*)

Theater System (Acoustic Cannon)

With the advent of digital cinema, speaker systems had to keep pace with improved audio content. Ken Jacob, at Bose, designed a system that consisted of a 12-inch woofer between two waveguides, totaling 150 inches in length (Fig. 21).[16] This system can create frequencies as low as 20 Hz. A typical installation would have two cannons

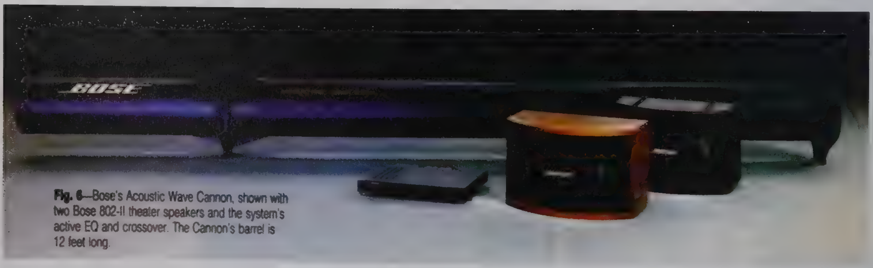


Fig. 6—Bose's Acoustic Wave Cannon, shown with two Bose 802-II theater speakers and the system's active EQ and crossover. The Cannon's barrel is 12 feet long.

Fig. 21. Theater sound system with the Acoustic Cannon. (*Audio*, Nov. 1991, p. 34)

with two Bose 802 speakers for midrange and Bose 102 speakers for the surround. This system has been installed in theaters in several states, as well as internationally.

Summary

The invention of the labyrinth speaker by Benjamin Olney was seminal in the development of transmission line speakers and future developments such as the Bose AWMS. I could not find a photograph of Olney. A collection of his papers resides at the University of Rochester.[17] I was able to find the following biographical note:

> *Benjamin Olney was born in Wayland, New York, on December 30, 1887. After graduating from Wayland High School in 1904, Olney worked for the Century Telephone Construction Company in Buffalo, New York until 1907, when he changed jobs to work for the Ingersoll Telephone Company. After leaving that position in 1920, Olney took the position of Engineer-in-charge for the Stromberg-Carlson Company's electrical laboratory. He worked for Stromberg-Carlson until 1950. During that thirty-year period, Olney founded an acoustical laboratory for the company and became the Director of Research.*

Upon retirement, Olney formed a partnership with Roy Anderson. Their company, Olney and Anderson, offered acoustical consulting services. During his career, Olney secured eight patents for inventions he made as contributions to the acoustical engineering industry. These included the Acoustical Labyrinth and a radio receiver. Olney was a member of the Institute of Radio Engineers, Acoustical Society of America, and represented Stromberg-Carlson at the Industrial Research Institute.

Olney was married to Mabel Gleason and died on May 16, 1963. Olney was responsible for setting up the audio group of the Institute of Radio Engineers (IRE), which later became the IEEE.

With copious information available on the design of TL speakers, I chose a few seminal works, to manage the size of this review and to enhance readability. The endnotes and references can be perused for more information.

Other Sources

1. F. A. Everest, K. C. Pohlman, *Master Handbook of Acoustics,* Fifth Edition (McGraw Hill, 2009). This is a classic handbook with a wealth of information on acoustics.
2. B. N. Locanthi, "Application of Electric circuit analogies to loudspeaker design problems," *Journal of Audio Eng. Soc.,* Vol. 19, Oct. 1971.
3. L. L. Beranek, *Acoustics* (McGraw Hill, 1954). He was a giant in the field of acoustics and his textbook is invaluable to those pursuing the field of acoustics.
4. This URL contains names of some of the other researchers and, sometimes, acrimonious relationships: https://www.wikiwand.com/en/Transmission_line_loudspeaker.
   - A. R. Bailey and Arthur Radford: They worked together and developed the concept for TL loudspeakers (1965). Their design was a significant

development from the earlier work. Bailey's name was on the article and Radford built the first commercial TL speaker.

- John Wright together with business partner John Hayes and (later) David Brown, and their company IMF Electronics Ltd (later: TDL). Wright, a "fanatical" pursuer of quality, had designed an award winning tone arm, and to demonstrate it, he brought to New York a non-commercial TL speaker that he had also designed. The speaker gained considerable attention and Wright, Hayes, and colleague Brown formed a company that specialized in TL speakers, and won numerous awards (1968). TDL disbanded following Wright's death in 1999 and the brand—as a shell—was bought by Richer Sounds.
- Irving M. "Bud" Fried–American audiophile and TL advocate, who encountered Wright and Hayes in 1968, recognized the potential of Wright's unnamed speaker, and began marketing their TL speakers in the United States. He later set up a TL company of his own to design speakers.
- Bo Hansson–Swedish designer of hi-fi equipment and founder of Opus3 Record Company, created the "Rauna Njord" concrete speaker as a transmission line design.
- Martin King and George Augspurger–researchers and designers who succeeded in modeling realistic TL speaker designs in the early 21st century.

Some of the companies that were involved in research and manufacture of TL speakers:

- Lentek
- Newtronics (Temperance line)
- Gini B+ (Bass Extenders line)
- Quadral
- T+A Electronics (Criterion line)
- J M Reynaud
- PMC
- Salk Sound
- Rega (their Naos then RS7)
- Adelaide Speakers
- TBI Audio Systems LLC (subcontracted by Asis to research and design smaller TL speakers suitable for embedding into laptops)
- Marantz (Karaoke range)
- Merkel Acoustic Research/Jeff Merkel
- Albedo (Helmholine range)
- Transmission Audio
- Audio Reference (Acoustic Zen line)
- Radford

DIY kit manufacturers:

- UK–IPL Acoustics (article), Falcon Acoustics "Thor"
- U.S.– GR Research "N3"
- U.S.–New York Acoustics, loosely associated with New York Audio Labs, kits and plans for 8-inch and 10-inch driver TL speaker cabinets; active in the mid 1980s.

Author's Note

Amar Gopal Bose (November 2, 1929–July 12, 2013) was an American entrepreneur and academic.[18] An electrical engineer and sound engineer, he was a professor at the Massachusetts Institute of Technology for over 45 years.[19] He was also the founder and chairman of

Bose Corporation. In 2011, he donated a majority of the company to MIT in the form of non-voting shares to sustain and advance MIT's education and research mission.[20]

Endnotes

1. B. N. Locanthi, "Application of Electric circuit analogies to loudspeaker design problems," *Journal of Audio Eng. Soc.* Vol. 19, Oct. 1971.
2. Benjamin Olney, "Sound Reproducing System," U.S. Patent 2,031,500, granted Feb. 18, 1936. https://patents.google.com/patent/US2031500. His main claim was for: Reduction of undesired resonances, i.e. standing waves within an enclosure, or of undesired vibrations, i.e. of the enclosure itself by means of the enclosure structure, i.e. strengthening or shape of the enclosure for loudspeaker transducers.
3. Ibid.
4. Amar Bose and William Short, in U.S. Patent 4,628,528, describe an invention for "Pressure Wave Transducing." This patent refers to the works of Olney and Bailey as well as others. Prior to the publication of this patent, there was a confidential internal technical report by Bill Short detailing the operation of the system.
5. A. R. Bailey, "A non-resonant Loudspeaker enclosure", *Wireless World*, Oct. 1965.
6. L.J.S. Bradbury, "The use of fibrous materials in loudspeakers," *Journal of the Audio Engineering Society*, Apr. 1976.
7. Amar Bose and William Short, "Pressure Wave Transducing," U.S. Patent 4,628,528, granted Dec. 9, 1986.
8. D. M. Pozar, *Microwave Engineering*, 4th edition (John Wiley & Sons Inc., 2011). I used this book for transmission line analogies and the behavior of short-circuited transmission lines.
9. http://mh-audio.nl/: This source has a wealth of information on loudspeakers and acoustics. Mobility models have mainly been used.
10. Thiele/Small parameters can be found in: https://en.wikipedia.org/wiki/Thiele/Small_parameters#:~:text=Thiele%2FSmall%20parameters%20(commonly%20abbreviated,performance%20of%20a%20loudspeaker%20driver. These are parameters used to describe low-frequency performance of a driver.
11. L.J.S. Bradbury, "The use of fibrous materials in loudspeakers."
12. For example, G. L Augspurger, "Loudspeakers on Damped Pipes," *Journal of Audio Eng. Soc.*, Vol. 48, May 2000. He used a lumped circuit mobility model to describe pipes of various shapes. He used a 32-stage lumped circuit model.
13. R. A. Robinson, Jr., "An Electroacoustic Analysis of Transmission Line Loudspeakers," Ph.D. dissertation, Georgia Institute of Technology, May 2007; https://smartech.gatech.edu/bitstream/handle/1853/14579/robinson_robert_a_200705_phd.pdf. In addition to compiling models and work on TL speakers, there is a detailed analysis and experimentation on fiberglass fillers. I have used impedance models and analogies from Robinson's work.
14. Amar Bose and William Short, U.S. Patent 4,628,528.
15. W. Short, personal communication, Bose Corp., 1984. Bill pointed out the differences between labyrinth speakers and the AWMS by using transmission line analogies.
16. W. Short, "Acoustic wave cannon for Bose cinema," *Audio*, Nov. 1991. Bill Short explains the acoustic wave music system and the Cannon, for cinema, in a simple way.
17. https://rbscp.lib.rochester.edu/finding-aids/D169
    Collection Overview. Title: Benjamin Olney papers; Creator: Olney, Benjamin, 1887–1963; Call Number: D.169; Dates: 1935–1963 [bulk], 1888–1963; Physical Description: 1.5 Linear feet; Language: Materials are in English.
    Abstract: The Benjamin Olney Papers document Olney's career as an acoustical engineer in the Rochester, New York area. Included in this collection are correspondence, design sketches, as well as industry periodicals and meeting programs. Repository: Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester.
18. https://en.wikipedia.org/wiki/Amar_Bose
19. "Amar G. Bose, Acoustic Engineer and Inventor, Dies at 83," the *New York Times* (July 12, 2013).
20. "Amar Bose '51 makes stock donation to MIT," Wikipedia, MIT, Apr. 29, 2011.

Acknowledgements

The works of several engineers and researchers have contributed to this review. At Bose, several discussions with

Bill Short and Amar Bose enhanced my understanding of TL loudspeakers and its variants. My group at Bose worked with Fuji-Electric in Japan for implementation and manufacture of the electronics. My thanks to the editors of the *AWA Review* for encouraging me to write this review.

About the Author

Sreeram (Ram) Dhurjaty was admitted to the Indian Institute of Technology, in Bombay, India at the age of 15. He continued at IIT, Bombay, until 1976, when he received a Doctorate in Biomedical Engineering. In 1976, he joined Yale University for a graduate degree in mathematical control theory. He was subsequently a postdoctoral fellow at Yale New Haven Hospital where he researched nuclear medicine instrumentation and early Computed Tomography (CT) Scanners. He occupied senior technical positions in industry. Over the years he worked at Analogic Corporation in Massachusetts, designing fetal monitoring systems, ultrasound imaging systems, and CT scanner front ends. He worked at Bose, on leave from Analogic, to understand acoustics and loudspeakers. He then worked at Eastman Kodak for 20 years, working on digital radiography. He was the primary inventor of the retrofittable x-ray radiography detector, which is now ubiquitous in radiology. At Kodak he had the title Technology-Guru. After leaving Kodak in 2005, he started a consulting company working on medical devices such as patient monitors, MRI systems, and x-ray generators. He holds 16 patents, including a patent (now expired) for a hand-cranked defibrillator. He holds a commercial pilot's license. At AAMI, he worked on writing standards for patient monitors and defibrillators. He has experimented with various loudspeaker systems during his career and holds an extra class ham radio license. He is a Senior Member of the IEEE, where he is the Distinguished Speaker for the Consumer Technology Society and a past chair of the IEEE Rochester section. He is an emeritus member of AAPM, member of AHA, AWA, and SPIE.

Sreeram (Ram) Dhurjaty

The "Ham" He Was: Robert F. Gowen

Part 1: The Early Years

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Robert Fellows Gowen (1883–1966) was an early radio pioneer who is little remembered today. Working for Dr. Lee De Forest, his inventions included the concept of the interpanel receiver (unit set), the honeycomb coil, and improvements to the audion. As supervisor of vacuum tube production, a thankless task, he was all that stood between De Forest and insolvency. An avid amateur, he pursued the ever-elusive DX, establishing experimental radiotelephony station 2XX at his home in Ossining, New York. He soon set distance records, reaching well-known amateurs like R.H.G. Mathews (9ZN) in Chicago and becoming one of the earliest radio broadcasters. Leaving De Forest's employ, he and his new bride headed to China where he would install radiotelephone stations in that then-turbulent country. Knowing not a word of Chinese, and with few supplies available, he was also tasked with writing a training manual and teaching the locals how to operate and maintain the stations, while for a time working for noted "warlord" Chen Jiongming. We begin the story of this remarkable life with his earliest radio experiments, his years at Harvard, and his initial experiences with Lee De Forest.

Introduction: A Covert Operation

Was anyone watching? The young men peered furtively out of the opening onto the steeply sloping roof of Weld Hall, one of the dormitory buildings at Harvard (Fig. 1).[1] The 20th century was only a few years old, and they were experiencing a strange, intoxicating mixture of excitement and fear, goading each other on. They knew what they had to do. They'd brought the equipment: ladder, rope, wire. An earlier request for permission had been denied and their previous secretive attempts were foiled by the steepness of the roof. This time they had an idea, and it would have to work.

After a few tries, they managed to lasso one of the big lightning rods successfully. Who said Ivy League kids

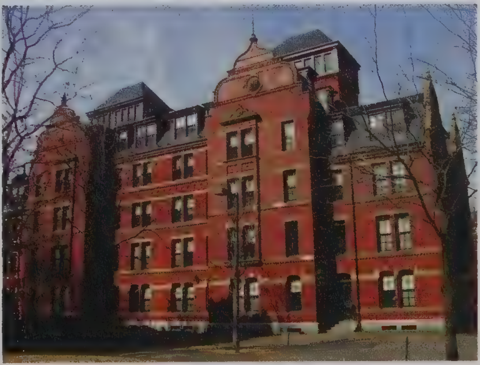


Fig. 1. Weld Hall, built in 1873, was briefly home to Robert Gowen and is still in use as a dormitory today. (Creative Commons License, https://creativecommons.org/licenses/by-sa/3.0/deed.en)

couldn't be cowboys? Now, using the rope as an anchor they were truly getting high—more than six stories up. Would it hold? They were betting life and limb on it. But steady nerves and steady balance saw them through, and in the end, they managed to pull it off. The aerial went up without a single casualty and nobody saw it or complained. Bob Gowen and his colleagues could race back to his room, disconnect the old antenna (a bed frame), hook up the new one, and try to eavesdrop on invisible signals traversing the ether from stations dozens of miles away.

A contraption-in-a-box that Gowen had assembled back home in Ossining, New York, and brought with him to college had become the "first radio set at Harvard" and the nucleus of the Harvard Radio Club. The triode detector had yet to be invented by Dr. Lee De Forest, whom Gowen would come to know and work for years later. Even the crystal detector was not yet widely known. So Gowen's 1904 receiver at Harvard featured a choice of then state-of-the-art detectors: two different Fessenden electrolytic detectors (built from cold creme jars) and a Massey carbon-steel (imperfect contact) detector. Although a bit more sensitive than coherers or Dr. Hertz's original detector, the spark gap, with no real means of signal amplification, these detectors required a strong signal and a long, high antenna to pick up signals. Hence their high-altitude adventure.

Similar feats of covert antenna erection would follow at colleges across the country as the "wireless bug" began to take hold from coast to coast. Out west in Berkeley, California, young Lewis Clement and Haraden Pratt would secretly string one from the top of the Campanile then under construction to the roof of an adjacent building, but that would not be until almost ten years later.[2] Gowen and his classmates had founded what was likely the first college radio club right there in Harvard Yard. It was another victory for the crimson, and may have helped stir up enough interest in wireless for the university to offer its very first class in the budding field, in which Gowen would assist instructor (later Professor) George Pierce. But who exactly was Robert Gowen?

Beginnings

Robert Gowen (Fig. 2) was born at a time when "wireless communication" probably meant writing a letter. He came into the world on December 30, 1883, almost three years before Heinrich Hertz first demonstrated electromagnetic

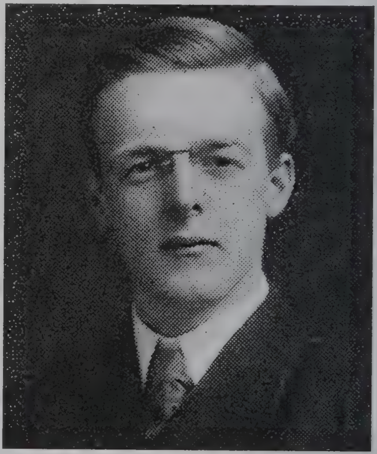


Fig. 2. Robert Fellows Gowen as he appears in the 1906 *Harvard College Yearbook*. (HUD 306.04, Harvard University Archives)

wave transmission and reception, about 18 years before Marconi succeeded in sending the first Morse character wirelessly across the Atlantic, almost 30 years before the HMS *Titanic* disaster made wireless telegraphy a topic of popular conversation, and about 40 years before many Americans would listen to their own radios. In other words, at the perfect time for a wireless pioneer to make an appearance. And with the initials RF, he was a natural!

Gowen was born in the industrial city of Lowell, Massachusetts, the first child of MIT graduate and New York civil engineer Charles Sewell Gowen and his wife Alice Jerusha Fellows.[3] The Gowens were fairly well-to-do, with one or two servants in residence for many years. By 1889 the family, which then also included Robert's sister, Mary, and would later include two more siblings, had moved to the village of Sing Sing, New York.[4] It was not until 1901 that the town would change its name to Ossining to try to distance itself from the prison that had made it well known.[5] Had he wanted to, Gowen could rightly claim to have gotten his education at Sing Sing!

His experiments in wireless probably began in 1902 when he built a coherer receiver and spark coil transmitter according to directions published by A. Frederick Collins, who, he noted, was "now in prison."[6] In his own words, "The first experiments of the author of any account… consisted of attempts to telegraph between his home and the grammar school, a distance of half a mile, and some radiotelephone experiments using induction coils between the front and back piazzas of the house. Just what degree of success was attained in these important researches is not recollected except that the grammar school stunt did not astound the physics class in its result. Although he has tried to live down the shame of it, the writer still refuses to be convinced that the old-style homemade Marconi coherer is a device fit to associate with radio receiving equipment."[7] He later reflected that his antenna, a one-foot square copper plate fastened to the chimney, might also have had something to do with it.[8]

But even failure could not dampen his enthusiasm for wireless. After graduating from Mount Pleasant Military Academy in 1902,[9] Gowen was admitted to Harvard, where his father wanted him to pursue a business education. Along with himself, he brought—Voila!—the first wireless set to be seen at Harvard. Or actually… the first wireless *transmitter* to be seen at Harvard, which seems to be the same portable half-inch spark transmitter with plate glass condenser that had let him down earlier.[10] Partly because permission to put an antenna atop Quincy Hall was denied, but mostly because there were no other amateurs in the immediate area to communicate with (he being the first), for some time this was only used as part of a Geisler tube display. Things changed when he moved to Weld Hall. By then rumors of reception of the Marconi South Wellfleet station CC (later WCC) began, and "the Fessenden electrolytic detector was coming into vogue."

Gowen visited CC in August of 1904 and met with Reginald Fessenden at his

Brant Rock station a year later. Soon, he converted Harvard's first wireless transmitter to Harvard's first wireless receiver which featured two of Fessenden's detectors (Fig. 3). He also wrote a paper, interestingly, on the priority of the electrolytic detector, a bone of contention between Fessenden and Dr. Lee De Forest.[11] Was Fessenden perhaps using the young man to help with his legal case, or did he just like reading that he was the first? Unfortunately, Gowen's paper, along with any information on what its conclusion was, appears to be lost. The courts would later award priority to Fessenden, but Gowen, as we will see, would end up working for De Forest.

He enrolled in Harvard's first radio physics course, given by an instructor (not yet a professor) named George Washington Pierce "and me."[12] Pierce (Fig. 4) was one of the luminaries of early radio who may have eventually "taught more eminent engineers than anyone in the world." His courses in radiotelegraphy were "the first to be given anywhere in the country," and became "the models upon which similar courses in other universities were built."[13] He would go on to become a full professor at Harvard, president of the Institute of Radio Engineers, and independently wealthy through his numerous patents including those on crystal-controlled oscillators.[14] He was an outstanding teacher, and his 1910 book, *Practical Wireless Telegraphy*[15] was arguably the best non-mathematical introduction to the science of radio of its day. For someone "obsessed with radio every minute of his life,"[16] Gowen again was at the right place at the right time.

He managed to get an "A" in Pierce's radio physics class, Physics 17, which was, in his own words, "the only A he ever got in college!"[17] A look at his academic records shows that this was no exaggeration.[18] Facing a curriculum heavy on language courses (French, German,

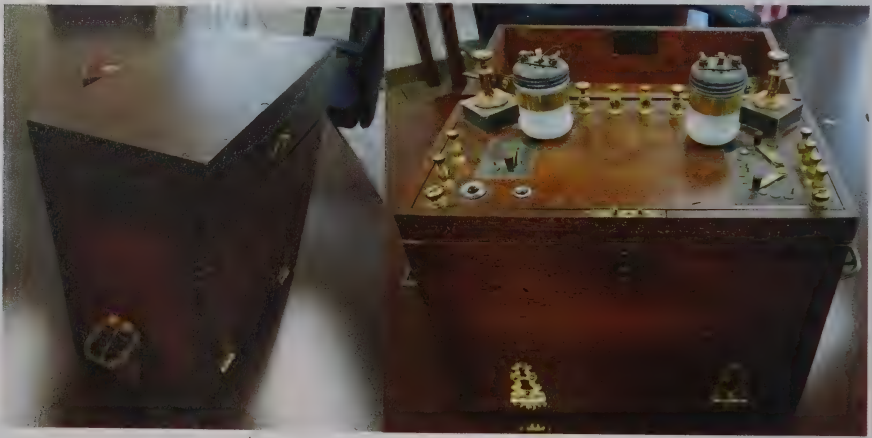


Fig. 3. This portable receiver built by Robert Gowen was used at Harvard circa 1904. Box closed and opened. Note the two electrolytic detectors made from cold cream jars. (American Radio Relay League)

Fig. 4. Professor George Washington Pierce taught the first radio class at Harvard. Photo taken circa 1930. (HUP Pierce, George W. (9b), olvwork245871, Harvard University Archives)

Latin, and Greek) which he rarely passed, the wonder was that he graduated at all, although he did graduate a year late due to academic probation. He did better in subjects he was interested in such as physics and engineering, and some letters in the Harvard files suggest that unspecified health problems may also have been involved. But it seems the most debilitating illness he had was the "wireless bug" that kept him dorm-bound and awake at all hours of the night with dots and dashes permeating his cranium. That disease was incurable.

The Weld Phonepterograph Company[19]

Before the rooftop aerial was put up atop Weld Hall, the bedspring antenna brought in exactly one station, the Boston Navy Yard (station PC), fully 5 miles away! After erecting the aerial, however, the results were disappointing until Gowen and fellow students, also bitten by the wireless bug, put together a tuning coil consisting of a three-foot wooden curtain rod wound with magnet wire and equipped with a slider (Fig. 5). This allowed them to home in on CC's long 2000 meter wavelength. The curtain rod tuning coil became standard equipment in other dorm stations that followed. And follow they did. Starting with stations A (Gowen and his roommate, R. H. Sheldon), B (Quincy Brackett, later a Westinghouse engineer), C (K. S. Johnson, later a Western Electric engineer), D (C. G. Goddard) and

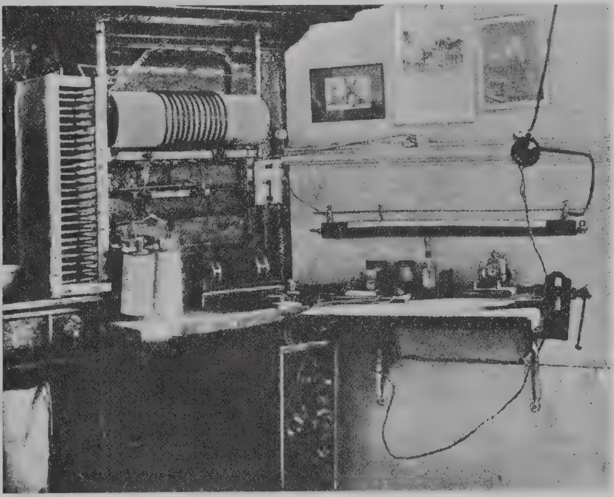


Fig. 5. A substation of the Weld Phonepterograph Company; note the long curtain rod tuning coil with slider above the shelf at right. (*Radio News*, September 1923, p. 244)

E (P. L. Moses), a total of 17 stations or substations (receive only) would eventually join up with the group (Fig. 6).

The fact that neither Gowen nor the others initially knew Morse code did not dampen their enthusiasm. Unlike Greek or Latin, he devoted many long hours to studying American and Continental code, soon becoming fluent in them, though he earned no course credits. A milestone was reached on November 21, 1906, when Station C (appropriately) copied CC's complete press news transmission. By that time, wireless excitement had resulted in the formation of the "Weld Phonepterograph Company of Harvard University," said to be the nucleus for the later Harvard Radio Club and the catalyst for Harvard's first radio class. The name "phonepterograph," meaning "to write with winged words," was coined by a Greek instructor and was not used before or since. Gowen was the organization's president and general manager. Letterhead ambitiously promising "Wireless Messages to All Parts of the Yard and Vicinity" was printed up.

Besides CC and the Boston Navy Yard, ships at sea could sometimes be heard. Interference was never a problem as the phonepterographists' activities

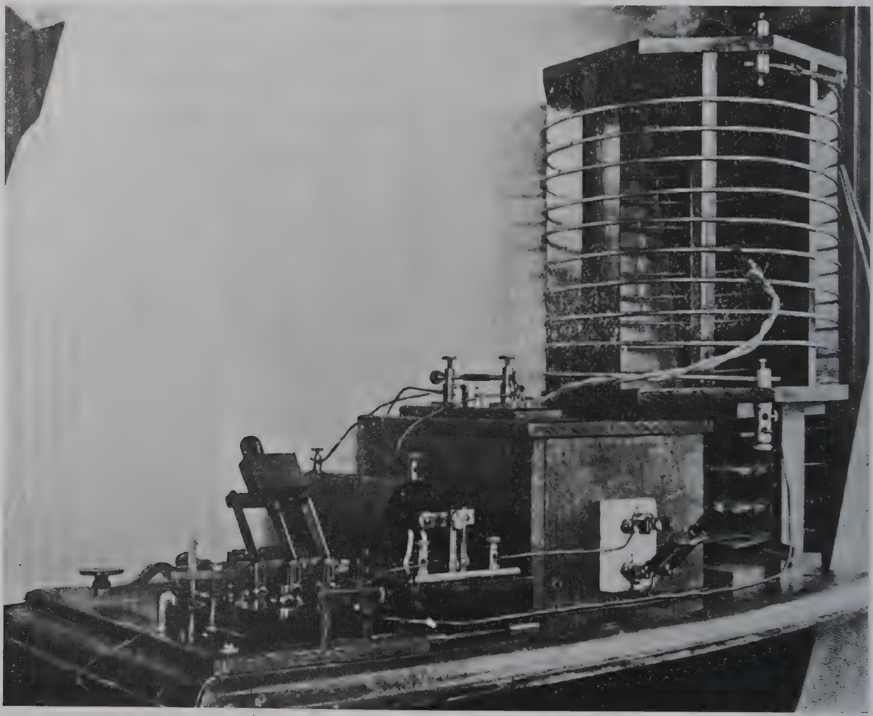


Fig. 6. Quincy Hall station. Note the camelback key on the lower left, the induction coil connected to the spark gap atop the wooden box, and the antenna helix upper right. (*The Harvard Illustrated Magazine*, March 1909, HUK 462 Vol. 10, Harvard University Archives)

were coordinated (many shared the same antenna) and there were few other stations nearby. Gowen sent out nightly orders at 2:30 a.m. forcing stations to shut down so sleep and perhaps studies would not be totally neglected. In his graduate year (1906–7) he moved off campus and upgraded his station from a half-inch Ruhmkorff coil to an eight-inch spark coil. This ran on city power (DC) fed into an electrolytic interrupter. Gowen noted that in those days no real attempt at tuning was made and transmission wavelengths, determined by the natural inductance and capacitance of the antennas, were probably in the 400–600 meter range (500–750 kHz).

Most phonepterograms were between students, and as you might expect, kind of frivolous. It is uncertain if they ever transmitted a message for a paying customer. At least one notable message was received, however. On January 23, 1909, by which time Gowen had left Harvard, Station A picked up a U.S. Navy order directing the wireless-equipped SS *Lebanon* to proceed to the aid of the SS *Republic*, which had just collided with the Italian steamer *Florida*.[20] This incident made Marconi operator Jack Binns famous and was one of the seminal events that impressed the general public with the lifesaving abilities of radio, which would be reinforced three years later by the HMS *Titanic* disaster.

Word of the Weld Phonepterograph Company soon got around, and on May 13, 1906, the *Boston Post* broke the story: "All the Members of 'The Winged Words Club,' Harvard's Newest Society, Know State Secrets!"[21] Navy transmissions were sent "in the clear" in those days since encryption/decryption was considered too burdensome short of war, so the perceived national security risk of young radio enthusiasts became a favorite topic from coast to coast. California amateurs Henry Heim Jr. and Albert Wolff Jr., as well as New Yorker Lloyd Espenschied, later received similar press coverage,[22] although doubtless without the florid prose of the *Boston Post* article: "The Weld Phonepterograph Company, Limited, marks the transformation of the Harvard Man's effervescence of youth from things earthly to things celestial."

Experiments At Harvard

During this time, Gowen, obsessed with things wireless, assisted instructor Pierce with his practical wireless research on the carborundum detector, later noting that he designed a crystal detector mounting adopted by Pierce and subsequently used on several Navy ships. Early wireless luminary Frederick Kolster was another member of the Pierce group. Gowen also carried out his own research, some of it to solve the most pressing issue of the day—inventing a better detector. In the entry for February 1906, he wrote: "While searching for a better detector than the electrolitic [sic], conceived of a tube type using radium or other radio active [sic] substances to shoot off a beam of electrons which was deflected by lines of force from a coil wound around the tube." It turned out to be impractical, he concluded, "as there was not enough radium in the world for the purpose."[23] This was probably lucky for him: exposure to radium could have horrific health consequences, a fact not yet appreciated back then.[24]

The other unmet need of the day was for a good radiotelephony system, and here too Gowen gave it the old college try. In his words, he "developed a radio telephone system dependent upon variation of electrode in electrolitic [sic] interrupter by means of voice currents." In addition, he "worked out a similar scheme using as an interrupter a column of mercury in a fine capillary tube which was heated by the current passing through it. Both schemes [were] abandoned as impractical due to the fact that audio frequency was employed, and the inertia of the electrical system was too great."[25] From these examples it appears that Gowen, like many early radio amateurs, was a "cut-and-try" inventor who approached problems by building things first and theorizing later rather than vice versa. This would later make him sympatico with De Forest, who also tended to invent in this Edison-like way.

Gowen also experimented with the "speaking" or "talking" or "singing" arc, a known technology at the time by which an electric arc acted as a loudspeaker, reproducing sounds like voice and music. Although this type of arc was the starting point for the invention of continuous wave radiofrequency transmitting arcs by Poulsen and others, it should not be confused with the latter.[26] Gowen, again in the third person, noted his "independent research on the speaking arc lamp during which he got hold of 500 volts and bought some rubber gloves." In demonstrating the arc, he was able to get enough volume of voice and phonograph music from the arcs to fill a large hall. As we'll see, experience with public demonstrations would play a role in his later career.

In his last years at Harvard, Gowen also assisted Professor Theodore Lyman IV, the discoverer of the "Lyman series" of hydrogen ultraviolet emissions lines. Here he studied the extremely short wavelength spectra of metals. In terms of radio activities, Gowen noted that he was invited to equip the SS *Newport* with wireless for its trip to the 1907 Jamestown Exposition. The ship would be carrying Massachusetts Governor (and Harvard alumnus) Curtis Guild to an exposition that featured an international naval review. Most likely, Pierce had proposed Bob Gowen as a good person to do the installation. Gowen had to decline, however, "because the State of Massachusetts would not insure the equipment."[27] On a less ambitious note, the previous summer he had installed an amateur radio station at the family's summer house on Cape Cod in Brewster, Massachusetts (Fig. 7), but found that with a half inch spark coil transmitter, there were no other amateurs close enough to contact. He later upgraded to a three inch spark coil but did not record whether or not that helped.

As we can see, Gowen's Harvard years were filled with wireless activities, scientific experimentation, and access to some of the leading scientists of his day. But as his academic days drew to a close, he faced the same challenge that every college graduate faces: What now?

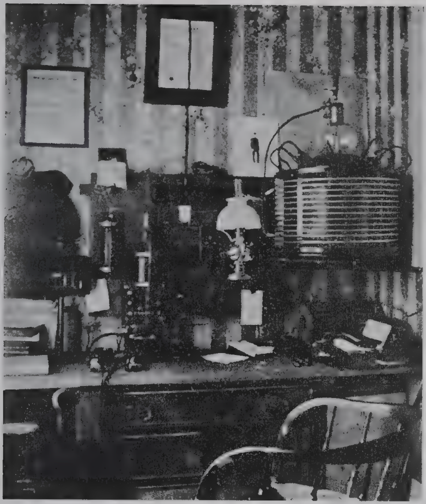


Fig. 7. Cape Cod station. Gowen's station at Cape Cod was later moved to his home in Ossining. The glass bulb above the helix at the right is a stationary spark gap. (*The Harvard Illustrated Magazine*, March 1909, HUK 462 Vol. 10, Harvard University Archives)

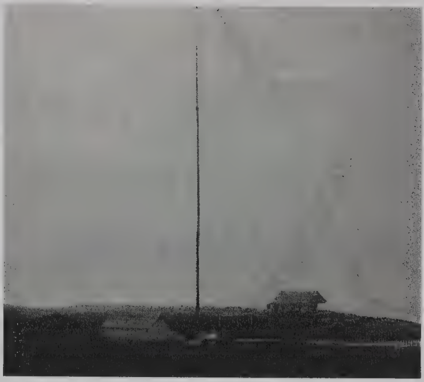
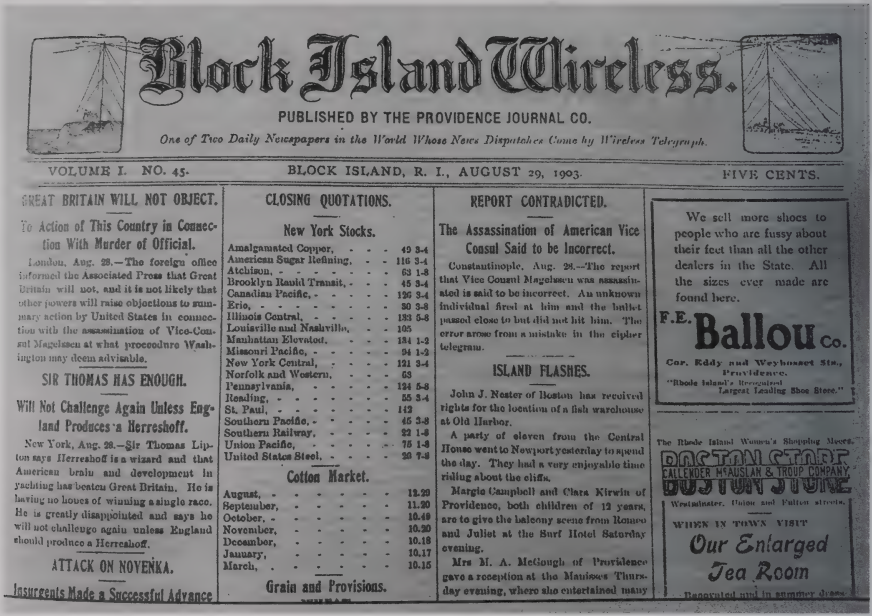


Fig. 8. De Forest radio mast at Block Island. The 200-foot mast of the wireless station rose to a higher elevation above sea level than any other object ever built on Block Island—350 feet including the height of the bluffs. Numerous supports and wires flow from it. The wireless station is left, and a summer residence is right. (Robert M. Downie, *The Block Island History of Photography*, Vol. 1, p. 176)

Post-College Years

According to Gowen, in 1907 he and his fellow Winged Words Club member Gardner T. Swarts, Jr. looked into buying the "old Massie Station at Block Island."[28] This is a bit puzzling since no Massie station appeared there until five years later! Most likely, Gowen was referring to the old De Forest station which dated from 1903 (Fig. 8). This was said to be a wonder of its day, attracting thousands of curious tourists.[29] It had been built under contract to the *Providence Journal* so that news from Point Judith on the mainland could be sent by wireless to the island (about 15 miles away) where a short newssheet, the *Block Island Wireless* would be printed up.[30] A storm had blown down the De Forest antenna, however, and the publication had only lasted for one summer, "publishing 45 issues between July 9 and August 29."[31] Part of the last issue printed is shown in Fig. 9. Gowen and Swarts were on a similar track "with the idea of receiving press from Point Judith (station PJ) by arrangement with the *Providence Journal*, headlines to be printed by them on backs of menu cards for hotels." It's unclear why this seemingly unambitious undertaking (headlines only?) was contemplated, but in any case, hotel managers failed to see the value of it, and Gowen and Swarts abandoned their efforts before any money was lost.

Swarts, as it turned out, was the son of Gardner T. Swarts, M.D., a prominent public health reform advocate who was secretary of the Rhode Island Board of Health for many years.[32] In February



Block Island Wireless.

PUBLISHED BY THE PROVIDENCE JOURNAL CO.

One of Two Daily Newspapers in the World Whose News Dispatches Come by Wireless Telegraph.

VOLUME I. NO. 45. BLOCK ISLAND, R. I., AUGUST 29, 1903. FIVE CENTS.

GREAT BRITAIN WILL NOT OBJECT.

To Action of This Country in Connection With Murder of Official.

London, Aug. 28.—The foreign office informed the Associated Press that Great Britain will not, and it is not likely that other powers will raise objections to summary action by United States in connection with the assassination of Vice-Consul Magelssen at what procedure Washington may deem advisable.

SIR THOMAS HAS ENOUGH.

Will Not Challenge Again Unless England Produces a Herreshoff.

New York, Aug. 28.—Sir Thomas Lipton says Herreshoff is a wizard and that American brain and development in yachting has beaten Great Britain. He is having no hopes of winning a single race. He is greatly disappointed and says he will not challenge again unless England should produce a Herreshoff.

ATTACK ON NOVENKA.

Insurgents Made a Successful Advance

CLOSING QUOTATIONS.

New York Stocks.

Amalgamated Copper,	49 3-4
American Sugar Refining,	116 3-4
Atchison,	63 1-8
Brooklyn Rapid Transit,	45 3-4
Canadian Pacific,	126 3-4
Erie,	30 3-8
Illinois Central,	133 5-8
Louisville and Nashville,	105
Manhattan Elevated,	134 1-2
Missouri Pacific,	94 1-2
New York Central,	121 3-4
Norfolk and Western,	63
Pennsylvania,	124 5-8
Reading,	55 3-4
St. Paul,	142
Southern Pacific,	45 3-8
Southern Railway,	22 1-8
Union Pacific,	75 1-8
United States Steel,	20 7-8

Cotton Market.

August,	12.20
September,	11.20
October,	10.49
November,	10.20
December,	10.18
January,	10.17
March,	10.15

Grain and Provisions.

REPORT CONTRADICTED.

The Assassination of American Vice Consul Said to be Incorrect.

Constantinople, Aug. 28.—The report that Vice Consul Magelssen was assassinated is said to be incorrect. An unknown individual fired at him and the bullet passed close to but did not hit him. The error arose from a mistake in the cipher telegram.

ISLAND FLASHES.

John J. Nester of Boston has received rights for the location of a fish warehouse at Old Harbor.

A party of eleven from the Central House went to Newport yesterday to spend the day. They had a very enjoyable time riding about the cliffs.

Margie Campbell and Clara Kirwin of Providence, both children of 12 years, are to give the balcony scene from Romeo and Juliet at the Surf Hotel Saturday evening.

Mrs M. A. McGough of Providence gave a reception at the Manisses Thursday evening, where she entertained many

We sell more shoes to people who are fussy about their feet than all the other dealers in the State. All the sizes ever made are found here.

F.E. Ballou Co.

Cor. Eddy and Weybosset Sts., Providence.

"Rhode Island's Recognized Largest Leading Shoe Store."

The Rhode Island Women's Shopping Mecca.

BOSTON STORE

CALLENDER McAUSLAN & TROUP COMPANY.

Westminster, Union and Fulton streets.

WHEN IN TOWN VISIT

Our Enlarged Tea Room

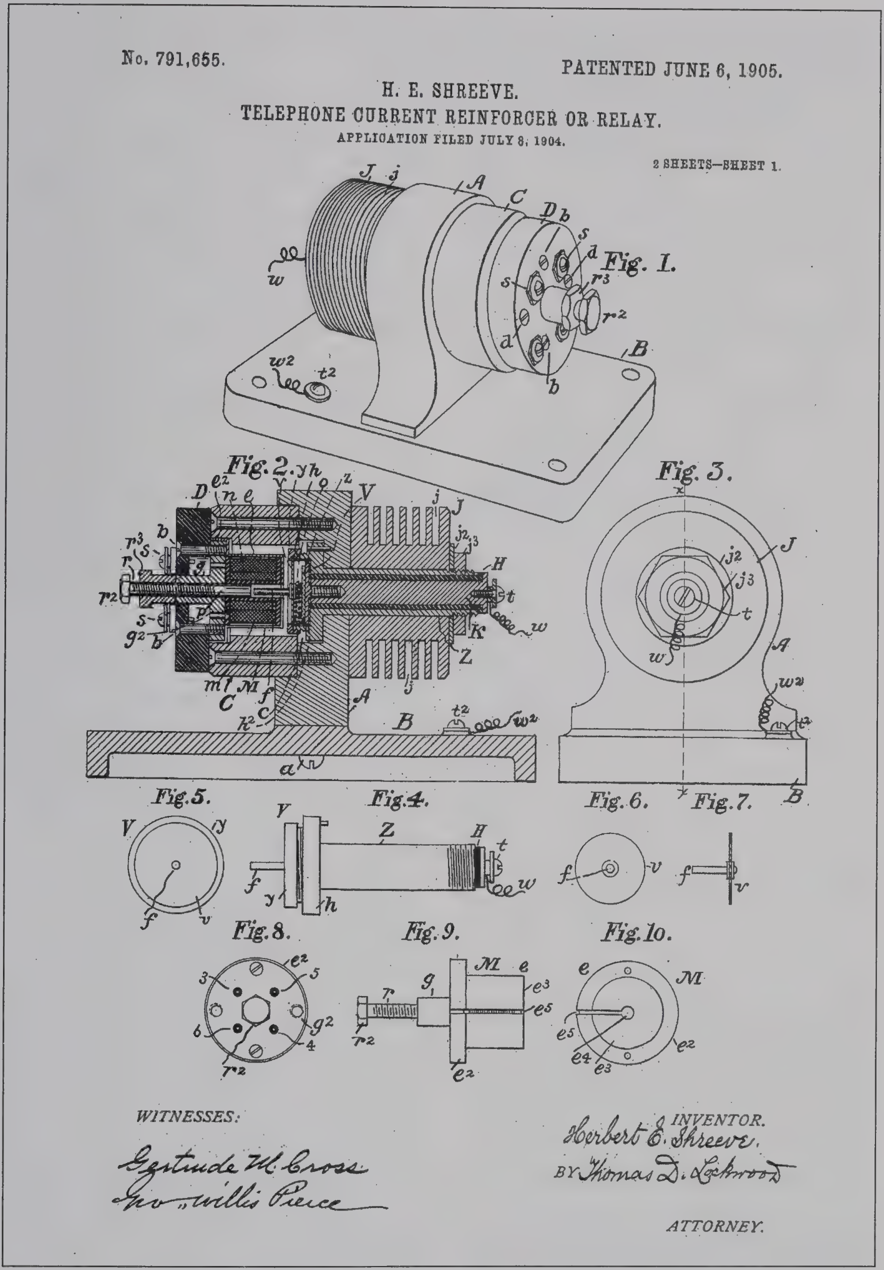
Fig. 9. Last *Block Island Wireless* newspaper issue, dated August 29, 1903. (Robert M. Downie, *The Block Island History of Photography*, Vol. 1, p. 177)

of 1908, Gowen joined that board with the title of Exhibit Manager, bringing with him a "practical, portable" speaking arc that could be used for demonstrations. Keep in mind that the modern loudspeaker would only be invented by Edward Pridham and Peter Jensen some seven years later; before that, getting enough volume for public addresses was challenging. Gowen took his arc to cities in Rhode Island, playing phonograph records of lectures on health topics. He also demonstrated the speaking arc at the Boston "1915" Exposition of 1909 (yes, that's right),[33] for which Gardner Swarts Jr. acted as a docent for some displays.[34]

In 1909 Gowen went to work in the engineering department of AT&T in New York City. He wrote surprisingly little about what he did there, remarking only that he had worked with the audion and the Shreeve repeater (Fig. 10).[35] The latter was a carbon granule-based electromechanical device used for signal amplification in long-distance circuits.[36] Of course, De Forest's audion and its successors would soon replace all such devices. Gowen most likely beheld his first audion as part of his job at AT&T. We can only imagine the excitement this new technology must have produced in an amateur radio enthusiast like him.

Ham Radio Ala 1909

In 1909 Gowen moved his station from Cape Cod, Massachusetts to his home in Ossining, New York. His father had died unexpectedly in October of that



No. 791,655.

PATENTED JUNE 6, 1905.

H. E. SHREEVE.

TELEPHONE CURRENT REINFORCER OR RELAY.

APPLICATION FILED JULY 8, 1904.

2 SHEETS—SHEET 1.

WITNESSES:
Gertrude M. Cross
Geo. Willis Pierce

INVENTOR.
Herbert E. Shreeve.
BY Thomas D. Lockwood
ATTORNEY.

Fig. 10. Shreeve repeater. An early incarnation of the mechanical telephone amplification device that Gowen later worked on at AT&T. Patent No. 791,655, June 6, 1905, filed July 8, 1904. H. E. Shreeve, Telephone Current Reinforcer or Relay. (https://patentimages.storage.googleapis.com/1f/ac/6d/9f9bd3ca699531/US791655.pdf)

year,[37] and perhaps a sale of the summer house or the need to stay closer to home catalyzed the move. Gowen's pre-radio-law, self-assigned callsign was ZA, and his goal was "to cover the 30 mile range to New York City," not an easy thing to do at the time, although it turned out to be only a small first step in his years-long pursuit of the ever elusive distant contacts (DX).

At that time his transmitter consisted of an eight inch spark coil fed by an electrolytic interrupter, with a photographic glass plate condenser and a spark gap enclosed in a glass globe, while the receiver used a loose coupler and crystal detector.[38] "Those were the days," he later wrote, "in which the operating circuit was a very select one." It consisted of a Mr. Runyan in Yonkers (15 miles), George Cannon in New Rochelle (25 miles), and finally Johnny Grinnan in New York City. Most helpful of all was Nyack ham Brainard Foote (only 5 miles away), later the radio editor of the *New York Evening Mail*. If Foote could be raised, "it meant that ZA was working."

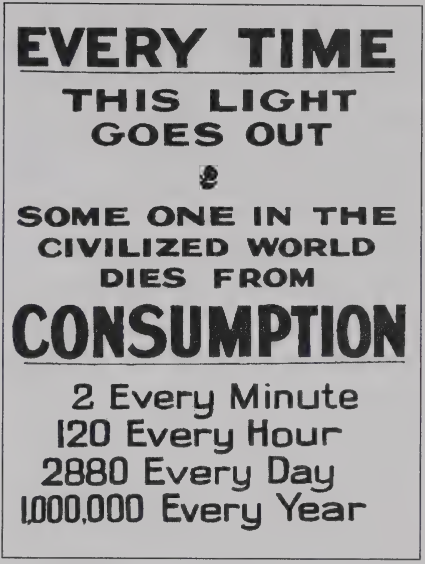
Gowen was finally able to confirm contacts (QSL) with stations in the Big Apple after upgrading his spark coil to a homemade transformer, "which had the very peculiar habit of persistently kicking back and blowing the electric light circuits all over the house." "Many and devious were the paths to ground" that it found, and the most problematic was in an outlet behind his mother's bed, which required two kickback preventers (RF chokes). Installing these was much easier than trying to convince her that there was no fire inside the walls. Even with all these precautions, he "never dared yield to the temptation to 'open her up' beyond a certain limit."

Ham radio circa 1909 was very different from what it would later become, and Gowen chronicles many of what would come to be considered its early peculiarities. Aside from the absence of vacuum tubes and any U.S. radio laws, there was no "traffic work" because in most places amateurs were too few and far between to make for reliable long-distance relays. "Traffic work was also impractical because everyone operated on any old wavelength and these wavelengths were liable to change from day to day so that one was always hunting for them—no small job with the tuners then being used," he wrote. Within a couple of years, however, the situation had improved. A break-in system using a carborundum detector allowed Gowen and Runyan to ask each other (in code) the eternal ham question, "How do you get me now?"

Electrical Exhibitionism

Gowen's AT&T employment lasted less than three years. In September of 1912 he left that position to once again team up with his friend Gardner Swarts Jr., and this time their enterprise met with more success. Their partnership was in a company that Swarts Jr. had founded known as the Educational Exhibition Company of Providence, Rhode Island. Gowen had also sent out feelers to V. Ford Greaves of the Department of Commerce and Labor (then in charge of radio regulation) concerning a possible position as a federal radio inspector, a position that had opened up with the passage of the 1912 Radio Act. Nothing, however, had come of this.[39]

Today, having a company based on educational exhibits sounds a bit odd, with a niche market at best, but the situation was very different in those years of the "progressive movement." The driving force was the sorry state of U.S. public health back then. In the America of 1900, more than one in seven newborns never lived to see their first birthday; the top three causes of death were all infectious diseases, with tuberculosis being the second leading cause just behind pneumonia/flu.[40] Since antibiotics would not be available for another 30–40 years, the best that could be done was to try to prevent disease transmission by improving public sanitation (e.g., clean drinking water and functioning sewers) and educating the public on hygiene, especially what to avoid (e.g., everyone drinking from the same cup).



EVERY TIME
THIS LIGHT
GOES OUT
SOME ONE IN THE
CIVILIZED WORLD
DIES FROM
CONSUMPTION
2 Every Minute
120 Every Hour
2880 Every Day
1,000,000 Every Year

Fig. 11. No. 514, Flashlight Death Rate Sign. A flashing sign was available for $25.00 from Swarts' and Gowen's Educational Exhibition Company for use in a tuberculosis exhibit. (*Educational Exhibitions Catalog C*, February 1914, p. 61)

The Educational Exhibit Company filled the growing demand for the latter with sometimes electrified, often mechanized creative exhibits. They sold "models, photographs, charts, lantern slides, moving apparatus, and cases to hold such material during transportation," used by "health boards, societies, and educational institutions for the education of the public on such topics as tuberculosis, clean milk, mosquitoes, and flies as disease carriers, water supplies, housing, and civics."[41] One of their simpler exhibits was a flashing sign marking tuberculosis deaths (Fig. 11). More elaborate displays included a six foot moving conveyor belt of dolls representing babies from birth to year one in which every seventh one disappeared, to be replaced by a pop-up gravestone (Catalog #5500) and "The Fly's Air Line" in which flies swarming over a manure pile enter an open, unscreened kitchen window to alight on the family dinner (Catalog #6506).[42]

Although it was probably fun to dream up and engineer these kinds of exhibits, for someone obsessed with amateur radio who'd been exposed to the glory of the audion, the electrical challenges involved would have seemed minuscule. Even worse, Gowen found that there was "no spare time and hence no amateur radio" during the four years he worked there.

For some of this time, he lived in Providence, away from his ham shack in Ossining,[43] and he may have had to travel as part of his job. One intriguing possibility is that this could have led to his first meeting with De Forest. The Educational Exhibition Company was heavily involved in displays for the Panama-Pacific International Exhibition in San Francisco in 1915,[44] at which the De Forest Radio Telephone and Telegraph Company was an exhibitor. In fact, De Forest himself hurriedly put together a brochure, "The Story of a Great Achievement" that outlined the importance of his audion in transcontinental telephony to counter "The Story of a Great Achievement" that AT&T was distributing, which failed to mention this.[45] (You have to admire his panache!) With De Forest present at the expo and with Gowen having worked for AT&T on the audion, it's almost inconceivable that if he were there he would not have looked De Forest up. But no record of this has been found, so it's only speculation.

What we know for certain is that Gowen left his position at the Educational Exhibition Company and returned home to Ossining in early 1916.[46] There "the radio bug immediately appeared again and attempts were made to read up [on] everything that had been missed." He spent a few weeks "endeavoring to make audion oscillate" for heterodyne reception of signals from an AT&T radiotelephone test being conducted for the Navy.[47] The shoreside transmitter, in a sort of brute force arrangement, used several hundred pliotrons connected in parallel to allow communications between Washington, DC, (via landline to Arlington, Virginia) and the battleship *New Hampshire*. The tests took place on May 6–8, 1916 (Fig. 12).[48] "It was a great day when the test finally came off," Gowen wrote, "and it was found that the computations were accurate to the extent that every word of the conversation between Washington

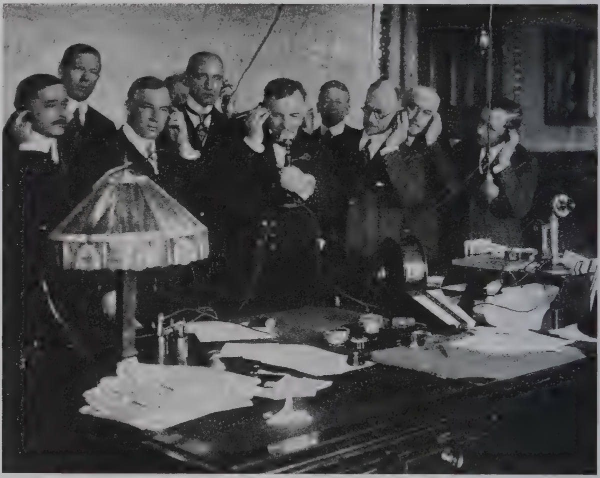


Fig. 12. Radiotelephony test. Along with Secretary of the Navy Josephus Daniels and the others shown here, Robert Gowen was able to listen in on this early radiotelephony test from his location in Ossining, New York. Label at bottom states "Talking to the U.S.S. *New Hampshire*, in Hampton Roads, by wireless telephone from the Navy Department, Washington. Secretary Daniels with transmitter, J. C. Carty at his extreme left, and E. N. Bethal at his right. Capt. Bullard, U.S.N., second to the left of the secretary." (*Electrical Experimenter*, July 1916; collection of Eric Wenaas)

and the battleship *New Hampshire* was clearly heard… This was the writer's first experience with radio telephony and it had the effect of increasing his enthusiasm…"

A Job In Radio

Whether motivated by a desire to support his mother and siblings after the early death of his father, a strong personal work ethic, a desire to be closer to the exciting developments in radio engineering, or maybe some combination of all three, Gowen never stayed jobless for long. In 1916 he once again started pounding the proverbial pavement, this time bound and determined to work in radio. He did what most of us have probably done at some point: used whatever connections he had, stretched the truth about his qualifications a little, and hinted that other offers might be in the works.

In a letter Gowen addressed to Edward J. Nally, president of American Marconi (who was actually its vice president at the time), he mentions a recent visit to Harvard where Dr. Pierce "has suggested an attractive proposition to me," as well as some friends "who are anxious to have me develop this laboratory idea with them to a business of large proportions."[49] Should American Marconi have an offer for him, perhaps he would consider it. He may have actually gotten one, since he later told his friend Quincy Brackett that Marconi was "down and out because of the war," and could not offer him any "decent money" since their highest-paid engineers "outside of Shoemaker" were paid just $18 per week.[50]

The first communication between Gowen and De Forest that we have is a letter dated September 5, 1916, referring to their prior telephone conversation of August 26. Gowen enclosed his radio resume (unfortunately lost) and offered to come to De Forest's New York lab.[51] This bait drew just a nibble. De Forest responded three days later saying Gowen appeared to be well qualified but there were no openings at that time, and he emphasized that he could not make any promises for the future.[52] But by September 23, Gowen believed he'd secured a job with De Forest (Fig. 13).

Gowen wrote to G. Brandreth Larkin, who must have been a neighbor and friend (and later worked at AT&T for many years).[53] He mentioned that his new job as a laboratory assistant for Dr. De Forest started October 2. "He has a fine lab there at High Bridge [in New York] with a lot of wonderful stunts in

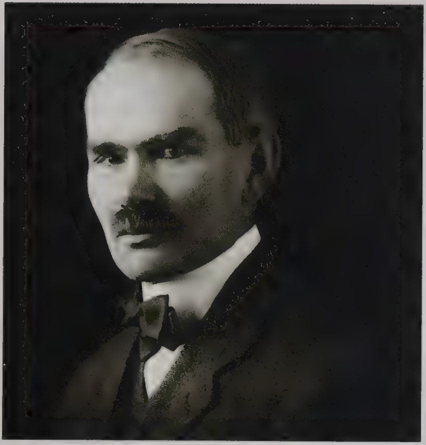


Fig. 13. "Father of Radio," and inventor of the audion, Dr. Lee De Forest, for whom Robert Gowen would work in the years around WWI. (Society of Wireless Pioneers)

process. Also has a large factory there producing a pile of new apparatus for the Govt. which I and another young fellow [Charles V. Logwood] are to have the pleasure of testing." He marveled at the audion "about 4 inches in diameter on a panel about 2 feet square that will send at least 500 miles on a half kW input." He also mentioned his own ongoing research on tuning coils and that Lounsberry, an Ossining neighbor who would also work for De Forest and later become a broadcasting executive,[54] "is getting everything from A to Z on his tube (set)."

That same day Gowen also wrote to his fellow phonepterographist, Quincy Brackett, who had previously worked for De Forest but was by then employed at Westinghouse.[55] Earlier, he had written him to ask about a job at Westinghouse, but had not heard back. His focus was now on what Brackett could tell him about De Forest. "After bickering all summer with the Marconi Co.," he mentions, "I accepted an offer last week to go in with Dr. De Forest." He had some reservations, though, and was anxious to get Brackett's opinion of his potential new boss: "Do you know what kind of fellow he is?" Among his concerns about De Forest was that "his reputation is very poor as to divorce, etc. I understand that he has made two or three business failures," though Gowen "thought that you [Brackett] believed that these failures were due to his business associates and not to De Forest entirely."[56]

First Impressions

Having asked what Brackett thought of him, Gowen gave his take on the inventor of the triode: "Doc struck me as being a very pleasant man to work for, very capable as a scientist and sincere in what he undertakes alone. On the other hand, he appears to be a very poor business man [sic], lax as to discipline, and with a weak personality… He appears to be one that might be easily influenced by unscrupulous promoters…"

Could the unsavoriness associated with De Forest possibly rub off on him, Gowen wondered? "Can you tell me what the wireless people such as Pierce and Kennelly think of him? What would my association with him mean as to getting another radio job later with someone else?" And there were short-term doubts: "He told me that he was having a hard time getting along as he had no cash available to pay me the salary I wanted at present…. He said that he had 65,000 dollars' worth of contracts on hand at present and a payroll of over a thousand a week and that the only way he could keep going was to get some of the stuff out quickly and get his money on it…." Gowen asked Brackett to give him the "inside dope." Did he think De Forest was going to "bust up again soon?"

We do not have Brackett's reply, but a big surprise was in store for Gowen the day before he was to start his job there. On September 30, 1916, De Forest wrote him a letter. "You doubtless know that we have lost our suit in the lower court on the Audion-Valve Litigation… This puts a bad crimp in our business… it also makes it impossible at this time to increase our payroll in any way. We find it therefore impossible to take you on at this time."[57] Gowen's reply expressed his disappointment, but also understanding of the situation, and his hope that things would improve so that he could be working there soon.[58] Reservations or not, he had not given up on working for De Forest.

And so it happened. About a month later in a letter to Brackett, Gowen said that he'd "bummed around all the month picking up all the odd jobs I could find and finally got hold of him [De Forest] again with the result that I went to work for him on Nov. 1st instead."[59] De Forest had offered to "put him on trial" at $15 per week, promising that there would be a multiplicity of duties.[60] Results of that trial, along with the stream of contributions Gowen would make to the development of radio in the United States will be the subject of Part 2 of this series.

Acknowledgments

Special thanks to Eric Wenaas (AWA) for suggesting this subject and supplying otherwise unavailable materials. Grateful acknowledgment is also due to Patty Sacchi (Ossining Historical Society Museum), Len Arzoomanian (RhodeIslandRadio.org), Ed Hare W1RFI and Maty Weinberg (both ARRL), Bart Lee K6VK and Mike Adams (both CHRS), Brian Wallin, Robert M. Downie, and the outstanding reference staff of the Harvard University Archives.

Endnotes

1. R. A. Morton, "The Wireless at Harvard," *The Harvard Illustrated Magazine*, Vol. 10, No. 5, Mar. 1909, pp. 131–5; R. F. Gowen, "The First College Radio Club," *Radio News*, Sept. 1923, pp. 244–96.
2. H. Dickow, "Tales of the Wireless Pioneers: The Story of Haraden Pratt – Pioneer," *Sparks Journal*, Vol. 7, No. 3, Mar. 1985, p. 9. Available at: http://www.silentkeyhq.com/wireless_archive/SOWP/Vol7No3.pdf.
3. "Births in the City of Lowell in the Year 1883," in *Massachusetts Births and Christenings, 1639–1915*, p. 183; The Gowen Manuscript Page, available at https://sites.rootsweb.com/~gowenrf/Gowenms081.htm.
4. Twelfth Census of the United States (1900), Schedule No. 1, State of New York, Westchester County, District No. 3, enumeration district No. 105, sheet No. 11. Robert and Mary Gowen are listed as being born in Massachusetts while John (born 1889) and Alice (born 1895) are listed as being born in New York.
5. See https://www.villageofossining.org/about/pages/ossining-brief-history.
6. R. F. Gowen, "R.F.G. Autobiography," p. 1. Document in the collection of the Ossining Historical Society Museum (hereafter called OHSM), Ossining, NY; R. F. Gowen, "Radio Biography of Robert F. Gowen," p. 1, OHSM. The article Gowen followed in building his station may have been A. F. Collins, "How to Construct an Efficient Wireless Telegraph Apparatus at a Small Cost," *Scientific American*, Sept. 14, 1901.
7. R. F. Gowen, "2XX", Ossining-on-Hudson, N.Y.: An autobiography of the author's amateur experience which was responsible for his being the pioneer in long-distance telephone transmission on low power and culminated in his broadcasting the first radio vaudeville show, dated May 14, 1923, p. 2, OHSM.
8. R. F. Gowen, "The First College Radio Club," op cit.
9. "Gowen, Robert Fellows," in *Who's Who in America,* Vol. 30, 1958–9, (A. N. Marquis Co., Chicago, IL) p. 1074.
10. Gowen, "The First College Radio Club," op cit.
11. Gowen, "R.F.G. Autobiography" op cit. p. 2. Gowen misspelled "electrolytic" as "electric" here.
12. Gowen, "R.F.G. Autobiography" op cit.
13. Orrin E. Dunlap, Jr., *Radio's 100 Men of Science* (Harper & Brothers, NY, 1944), pp. 161–4.
14. D. Wunsch, "Harvard's Radio Past: A Sort of Memoir," *AWA Review*, Vol. 32, 2019, pp. 1–28.
15. G. W. Pierce, *Principles of Wireless Telegraphy* (McGraw-Hill, NY, 1910).
16. Gowen Research Foundation Newsletter, Vol. 10, No. 3, Nov. 1998. Available at

https://goyengoinggowengoyneandgone.com/1999-11-nov-newsletter-grf/.
17. Gowen, "Radio Biography of Robert F. Gowen," op cit., p. 1.
18. Harvard University, UA III 15.88.10, Student Folders, Robert Fellows Gowen – A.B. 1906(07).
19. Information for this section comes from six sources: R. F. Gowen, "The First College Radio Club," *op. cit.*, "R.F.G. Autobiography," op cit., "2XX," *op. cit.*, "Radio Biography of Robert F. Gowen," (OHSM); R. A. Morton, "The Wireless at Harvard," *The Harvard Illustrated Magazine*, Vol. 10, No. 5, Mar. 1909, pp. 131–5; and "All the Members of 'The Winged Words Club,' Harvard's Newest Society, Know State Secrets," *Boston Sunday Post*, May 13, 1906. Where sources disagree best judgment was used.
20. J. Binns, V. U. Lovelace, "Wireless and the Sinking of the *Republic*, 1909," *AWA Review*, Vol. 23, 2010, pp. 239–272.
21. "All the Members of 'The Winged Words Club' Know State Secrets," op cit.
22. See R. M. Rydzewski, "The Wireless Boys of Alameda: Part 2 – There Ought To Be a Law," *Journal of the California Historical Radio Society*, Fall 2022.
23. Gowen, "Radio Biography," op cit., p. 1.
24. In 1934, Maria Sklodowska-Curie (Madame Curie) died of aplastic anemia caused by long-term exposure to radium, which damages the bone marrow tissue responsible for producing blood cells. The "radium girls" who suffered debilitating bone loss, disfigurement, and cancer after painting glow-in-the-dark watch dials with radium paint did so in the 1920s.
25. Gowen, "Radio Biography," op cit., p. 1.
26. See W. J. Byron, "The Arc Method of Producing Continuous Waves," *Antique Wireless Association Review*, Vol. 7, 1992, pp. 119–150, and L. R. Mateo, "The Arc Radio Transmitter," available at https://www.sowp.org/wp-content/uploads/2022/08/LR-9908172203-Mateo-Arc-Article.pdf.
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28. Gowen, "Radio Biography," op cit., p. 3.
29. "Running a 'Wireless' Daily Paper on Block Island," *Providence Sunday Journal*, Sept. 13, 1903.
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37. "Memoir of Charles Sewall Gowen," *Proceedings of the American Society of Civil Engineers*, Vol. 48, No. 7, Sept. 1922, pp. 1642–6.
38. Gowen, "2XX," op cit. p. 4.
39. Letter from Robert Gowen to Mr. W. D. Terrell, Department of Commerce and Labor, dated January 29, 1913. From the collection of Eric Wenaas (hereafter referred to as EW).
40. See https://www.ncdemography.org/2014/06/16/mortality-and-cause-of-death-1900-v-2010/.
41. *Harvard College Class of 1907, op. cit.*
42. Educational Exhibitions Catalog C, Feb. 1914.
43. *1914 Providence City Directory*, p. 342.
44. J. L. Koslow, *Exhibiting Health* (New Brunswick, New Jersey, Rutgers Press, 2020).
45. *Lee de Forest, Father of Radio,* (Chicago, Wilcox & Follett, 1950) pp. 328–9; M. Adams, *Lee de Forest, King of Radio, Television, and Film,* (New York, Springer, 2012) pp. 152–3.
46. Gowen, "Radio Biography" op cit., p. 4.
47. Gowen, "2XX," op cit. p. 4.
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49. Letter from R. F. Gowen to Mr. E. J. Nally, Marconi Wireless Telegraph Co. of America, dated July 15, 1916 (EW).
50. Letter from R. F. Gowen to Quincy A. Bracket, Westinghouse Electric & Mfg. Co., dated Sept. 23, 1916 (EW).
51. Letter from R. F. Gowen to Lee De Forest, DeForest Radio Telephone & Telegraph Company, dated Sept. 5, 1916 (EW).
52. Letter from Lee De Forest to R. F. Gowen, dated Sept. 8, 1916 (EW).

53. Letter from R. F. Gowen to G. Brandreth Larkin, dated Sept. 23, 1916 (EW).
54. G. Dworshak, "Lounsberry a Pioneer in East," *Radio Digest,* Nov. 1929.
55. Quincy Adams Brackett entry, *Harvard Engineering Journal*, Vol. XI, No. 2, 1912, p. 137.
56. Letter from Gowen to Bracket, op cit.
57. Letter from Lee De Forest to Robert F. Gowen dated Sept. 30, 1916 (EW).
58. Letter from Robert F. Gowen to Lee De Forest dated Oct. 2, 1916 (EW).
59. Letter from Robert F. Gowen to Quincy Bracket dated Nov. 5, 1916 (EW).
60. Letter from Lee De Forest to Robert F. Gowen dated Oct. 24, 1916 (EW).

About the Author

Bob Rydzewski is a research chemist and medical writer who has been collecting radios since the turn of the (21st) century. He's never seen a tube radio he didn't like and has the overflowing garage to prove it. Reading the late Alan Douglas's great trilogy, *Radio Manufacturers of the 1920s* inspired him to research and try to document forgotten historical figures and events related to this great transformative technology. Bob is a member of the California Historical Radio Society where he is currently Deputy Archivist of the Society of Wireless Pioneers Archives (www.sowp.org). He and his wife live in the San Francisco Bay Area. In the accompanying photo, he is shown pretending to pilot a vintage U.S. Navy R6D on the beautiful island of Oahu.

Bob Rydzewski

Letter to the Editor

Re: *AWA Review*, Vol. 35, 2022, p. 192, Fig. 33 "…whose logo I have not been able to identify."

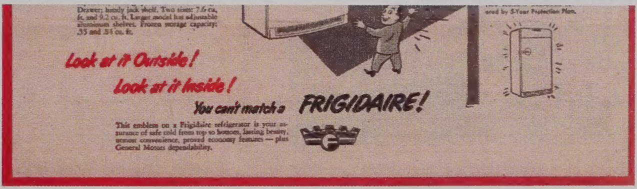
November 15, 2022
To: Editor, *AWA Review*

[Chuck Penson's article "The Simpson Micro-Testers: A Deconstruction of the VOM." Fig. 33 caption: Simpson made variations of the 385-3L branded for specific customers. Detail of the 385-3L meter scale (left) compared to a custom version for a customer whose logo I have not been able to identify.]

The logo in question is for 1950s vintage Frigidaire appliances. As a former General Motors engineer, I recognized it immediately and was able to find an actual advertisement from the era, to confirm that fact. See Fig. 1 for the logo advertising Frigidaire, and Fig. 2 for the meter in question.

I am an 83-year-old retired ME and have found the early work on spark transmission and reception especially interesting. As a new member of AWA (two years), I have been delighted by the level of historical detail that is provided by the AWA and in the *AWA Review.*

Many thanks.
H. F. Brown, Skaneateles, NY



Drawer; handy jack shelf. Two sizes: 7.6 cu. ft. and 9.2 cu. ft. Larger model has adjustable aluminum shelves. Frozen storage capacity: .35 and .54 cu. ft.

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Look at it Outside!
Look at it Inside!
You can't match a FRIGIDAIRE!

This emblem on a Frigidaire refrigerator is your assurance of safe cold from top to bottom, lasting beauty, utmost convenience, proved economy features — plus General Motors dependability.

Fig. 1. Logo advertising 1950s vintage Frigidaire appliances, from reader's Letter to the Editor.

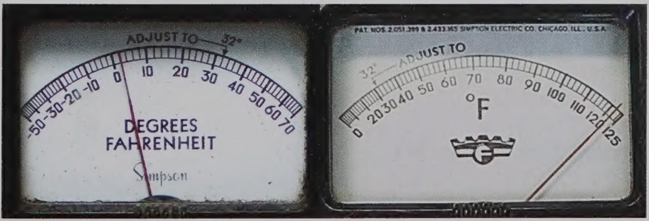

Fig. 2. The meter in question from Chuck Penson's article "The Simpson Micro-Testers: A Deconstruction of the VOM," in *AWA Review* Vol. 35, 2022.

Letter to the Editor

Received my *AWA Review,* Vol. 35, 2022 yesterday.

Hi Tim,

What a great idea it was of yours to position the article on mechanical television ["When Television was Just Around the Corner" by Michael Molnar] ahead of my article on Canadian television history ["A Short History of Canadian Television and Technology"]. What a great lead-in it made and was very complementary! I hadn't realized how much there was to mechanical TV history. Also, the Indian head test pattern and the color bar test pattern made for a great looking back cover.

Regards,
Jerry Proc

Letter to the Editor

Great story on mechanical TV! ["When Television was Just Around the Corner" by Michael Molnar]

Tuesday, August 16, 2022
Hello Michael [Molnar]

But you didn't point out that over in the UK, Logie Baird was using the "spotlight process" and the "intermediate film process" for his mechanical TV system, broadcasting as late as 1936 when the BBC decided that all-electronic TV would be the better way to go. See *The History of Television, 1880 to 1941* by Albert Abramson.

Appreciate all your research on such an interesting subject.

Best regards,
Richard Brewster, Cutchogue, NY

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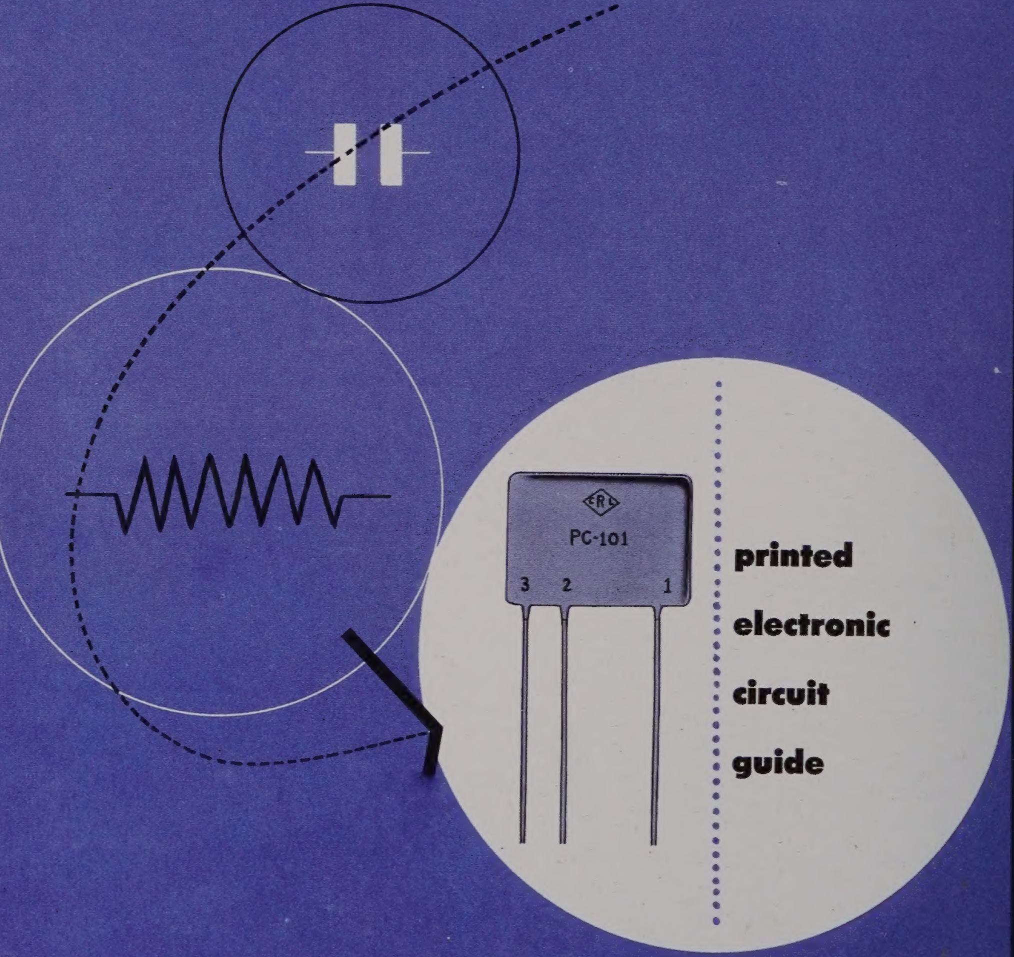

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